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Psychology & Philosophy

# Athletics and attention: Bi-directional influences in the lab and on the field

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**Abstract:** Selectively attending to some information while ignoring other information is crucial for athletic success. Active participation in athletics is also beneficial when attention is measured in the laboratory. This review examines this bi-directional relationship between athletics and attention. The introduction orients readers to the concept of selective visual attention. In the following section we review the evidence that athletic participation influences performance on laboratory measures of visual attention, including tasks of spatial orienting, spatial shifting, attention distribution, temporal sequencing, and the control of action. In the third section we review how attention measures are influenced by contextual factors that are also known to influence athletic performance. These include behavioral practices like exercise, sleep, and hydration; environmental factors like thermal stress, competition, and distraction; and individual differences in personality, age, and gender. In the next section we situate all this empirical evidence in the evolving theoretical understanding of attention in the cognitive sciences over the past five decades. In doing so, it becomes clear that research on athletics is an important database to consider when developing models of attention. By bringing these literatures together, a stronger theoretical foundation is sought that may contribute positively to research on both optimal athletic performance and framework development in attention.

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## Introduction

Visual selective attention, which involves privileging some information while ignoring other information, is critically important for success in sport. Depending on the sport, athletes must quickly orient to certain objects and locations, shift their attention in space and time, rapidly identify objects and spatial-temporal patterns, inhibit automatic responses in order to execute goal directed actions, and often do all this while simultaneously displaying misleading information to their opponents. This review examines the bi-directional relationship between sport and attention by considering how athletes of varying sports show differential performance on popular laboratory measures of attention (see section 2 Attention tasks and popular sports). In the next section (see section 3 Factors influencing athletics and attention in the field) we review contextual factors that are shown to influence both athletics on the field and attention measures in the lab. These factors include certain behavioral practices, specific environmental conditions, and some stable individual differences between athletes. This section therefore brings together evidence from historically-separate but theoretically-related literatures for the first time. In section 4 (The evolving nature of attentional theory) we review how theoretical frameworks for

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understanding attention have evolved over the past five decades in the cognitive sciences. These frameworks include the theoretical ideas of *saliency and priority maps*, the *integrated prioity map*, the *priority state space*, and a fully *dynamic* framework for attention. After reviewing how each framework conceptualizes attention, we consider how each is able to accommodate the evidence we have reviewed in sections 2 and 3. In doing so, it becomes clear that the literatures on optimal athletic performance and on selective attention mutually reinforce one another. We therefore encourage researchers in each of these fields to draw on these related literatures when developing new theoretical frameworks and ideas.

### *Attention*

What is attention? Over 130 years ago, William James (1890) wrote that attention always involves the interplay between two distinct human tendencies. One of these tendencies is to have attention be *pulled* to unique occurrences in the environment, including “strange things, moving things, wild animals, bright things, pretty things, metallic things, words, blows...and blood.” (p. 417). The other tendency is to have attention be *pushed* by the interests, intentions, and goals of an individual. Since then, theoretical frameworks of attention have contended in one way or another with this tension between the *pull* of attention by the external environment and the *push* of attention by the internal needs of the organism. In the theories of attention that dominated the cognitive sciences of the 20th century, the pull of attention was typically described as being external, effortless, reflexive, involuntary, and bottom-up. The push of attention, on the other hand, was characterized as being internal and top-down, involving knowledge, volition, effort, past experiences, and expectations (Eysenck et al., 2007; Pashler et al., 2001; Posner, 1980; Shiffrin & Schneider, 1977; Treisman & Gelade, 1980; Wolfe, 2010). Sometimes this push and pull dynamic of attention has also been characterized by the terms *endogenous* and *exogenous* attention (MacLean et al., 2009; Posner, 1980). These terms imply that selection can be driven by the internal endogenous processes of an individual (e.g. expectations and goals), or by external exogenous properties of the environment (e.g. unique brightness and color values).

Given the near-universal acceptance of the push-pull dynamic as central to understanding how attention is controlled at any moment in time, it is perhaps not surprising that many of the underlying behavioral methods used to study attention have been constructed to measure this dynamic. In light of this, some critics have accused research on human attention as being paradigm-bound and therefore tautological; attention is what attention tasks measure (Hommel et al., 2019; Ristic & Enns, 2015a). Sections 2 and 3 of this paper take a deliberately empirical approach in reviewing the most popular attention tasks and most popular sports, in order to provide readers with a high-level overview of the main findings. In section 4 we consider how this empirical research is accounted for by the various theoretical frameworks that have been proposed by

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cognitive scientists to understand attention over the past five decades. We conclude that empirical research on athletics and attention is both informed by, and informs, the parallel discussions that are going on among theorists who are all trying, in one way or another, to escape the paradigm-bound nature of attention research that has dominated the field for so many years.

### *Literature search methodology*

How can we summarize hundreds of studies in a brief review? We begin our review by considering research employing popular measures of visual attention that have been tested on athletes participating in a variety of sports. This strategy deliberately reflects the paradigm-specific nature of attention research. Table 1 shows the relative frequency of the various task-sport combinations in the literature, as determined by *Web of Science* searches conducted during August 2020. The first row in Table 1 contains labels that are widely held to be among the core constructs of visual attention. Each of these constructs are represented in the literature by specific behavioral tasks that are designed to measure the pull and push of attention with regard to that construct. Consider the first construct of spatial orienting. The detection of a target object in the visual field can come about because the environment pulls attention toward regions of the visual field that are unique based on features such as luminance, motion, color, size and/or shape. But it can also occur because the observer voluntarily pushes attention to a particular spatial location in order to extract region-specific information.

A similar distinction between the push and pull of attention can be made for the other tasks in Table 1. Consider the two popular tasks, visual search and Stroop. Visual search tasks range on a continuum from those in which the target simply pops out of the display, pulling attention toward itself, to tasks in which finding the target requires dedicated and concerted effort, requiring the systematic pushing of attention by the observer to different regions of the display until the target is found. A search task becomes more effortful directly as a function of how similar the target and distractor items are to one another (Duncan & Humphreys, 1989). In the Stroop task, the participant is asked to name the ink-color of a printed word (e.g., blue), when the word itself may spell a different name (e.g. "red"). There is a pull of attention to read the printed word because of overlearned reading habits, but the imperative task is to push attention to the ink-color of the letters.

Table 1 also reveals that researchers have focused on some measures of attention more than others. For instance, visual search tasks are popular in sport research, reflecting the popularity of these tasks for the study of attention more generally. And some sports have been the focus of attention research more frequently than other sports. Researchers often characterize sports based on the stability of the environments in which they occur (Highlen & Bennett, 1979; Poulton, 1957). Static sports are characterized by an environment that is relatively predictable and stable

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over time. These sports commonly emphasize execution of well-rehearsed closed-loop motor skills. Dynamic sports by contrast tend to occur in environments that are less predictable and require rapid adaption to ongoing gameplay. Dynamic sports often place greater demands on open-loop motor skills (Arvinen-Barrow et al., 2007; Coelho et al., 2007; Gu et al., 2019). Team field sports are therefore considered to be near the dynamic end of the spectrum whereas sports such as swimming and track are nearer the static end. Of the 18 sports listed in Table 1, the top 11 most frequently studied are dynamic, with the exception of golf. The higher frequency for golf is likely attributable to research on the quiet-eye. The disproportionate number of studies on dynamic sports also likely reflects researchers bias to think that dynamic sport environments place greater demands on attention than static sport environments. The appeal of testing athletes with these specialized skills offers a study sample where a putative cognitive skill has been honed to a high degree. This compliments the more common and traditional strategy of testing participants whose skills have been lost or impaired through brain pathology.

The relative counts in Table 1 also speak to the validity of linking sports participation with laboratory measures of attention. There are clearly hundreds of original studies establishing this link. However, as expressed by the term bi-directional in our title, we think it is likely that arrows of causality run in both directions. That is, individuals with relatively stronger attention skills, as measured by laboratory tasks of attention, are likely to perform better on the sports field than individuals with relatively weaker attention skills. Conversely, athletes who are demonstrably more skilled in their chosen sport are likely to perform better on laboratory tasks of attention than athletes that are less skilled. Indeed, a feed-forward cascade is likely in play, such that while participation in sports may initially be seeded by individual capacities of attention, these capacities are then strengthened further by participation in sport.

We caution that the frequency values in Table 1 should not be considered as an exclusive categorization of sport types, attention measures, or journal articles. There is possible overlap in these numbers, because some journal articles refer to more than one sport and also to more than one measure of attention. Some of these articles may also mention a specific measure of attention and sport, but only as an implication or suggestion in light of a more disparate topic under study. The tabled values simply represent the number of peer-reviewed journal articles that make reference in their titles, abstracts, and key-words to the particular conjunctions of terms given in the rows and columns of the table. These results are also based on a single search engine, *Web of Science*. As such, we offer these data as an approximate indication of the relative frequency with which these concepts have been combined in scholarly articles.

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**Table 1**
The frequency of articles reported by Web of Science to contain the conjunctions of sports terms and attention measures in the titles, abstract and keywords. Attention measures are grouped into constructs that form the basis of many theoretical frameworks for attention. The search was conducted in August 2020, using the advanced search function in the Web of Science Core Collection, for English-language peer-reviewed articles in the period 1920-2020.

| Sport | Orienting | Shifting & tracking | | | Breadth | | Attentional control | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Posner or spatial cueing | Visual search | Trail making | Multiple object tracking | Useful field of view | Perimetry | Stroop | Flanker | Stop signal | Quiet-eye | |
| **Soccer** | 2 | 190 | 1 | 18 | 1 | 1 | 24 | 2 | 3 | 18 | 260 |
| **Tennis** | 4 | 127 | 0 | 2 | 1 | 0 | 10 | 2 | 1 | 11 | 158 |
| **Football** | 1 | 66 | 2 | 7 | 0 | 1 | 13 | 5 | 0 | 1 | 96 |
| **Basketball** | 2 | 45 | 0 | 9 | 0 | 0 | 12 | 3 | 2 | 18 | 91 |
| **Golf** | 1 | 12 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 28 | 42 |
| **Baseball** | 0 | 29 | 1 | 1 | 0 | 0 | 1 | 1 | 4 | 3 | 40 |
| **Volleyball**[a] | 3 | 28 | 0 | 2 | 1 | 0 | 1 | 1 | 0 | 0 | 36 |
| **Handball** | 0 | 25 | 0 | 1 | 0 | 1 | 5 | 1 | 1 | 1 | 35 |
| **Hockey** | 1 | 15 | 1 | 7 | 0 | 1 | 4 | 0 | 0 | 4 | 33 |
| **Rugby** | 0 | 19 | 0 | 2 | 0 | 0 | 6 | 1 | 0 | 2 | 30 |
| **Cricket** | 0 | 21 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 24 |
| **Track & field** | 0 | 6 | 0 | 8 | 0 | 0 | 1 | 2 | 0 | 2 | 19 |
| **Ski** | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 7 |
| **Jog** | 0 | 1 | 1 | 0 | 0 | 0 | 3 | 1 | 0 | 0 | 6 |
| **Bike & cycle** | 0 | 1 | 1 | 0 | 0 | 0 | 2 | 1 | 1 | 0 | 6 |
| **Skate** | 0 | 2 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 5 |
| **Swim & pool**[b] | 0 | 4 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 5 |
| **Weight lifting** | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| **Total** | 14 | 598 | 7 | 60 | 4 | 4 | 84 | 20 | 13 | 90 | 894 |

[a] Includes squash and racquetball. bExcludes rat research.

## Attention tasks and popular sports

### *Spatial orienting*

What are the consequences of orienting visual attention to specific regions of space? Orienting attention to certain spatial locations while ignoring other locations is critical for success in many sports. For example, volleyball athletes need to keep track of the spatial pattern of players on the other side of the net, while simultaneously orienting their eyes and actions with respect to the ball they are about to strike. When striking the ball, voluntarily pushing one's attention to its current location, while attempting to ignore the pull of attention to the sudden movement of

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an opponent can be the difference between a kill and a whiff. Given such attentional demands, Castiello and Umiltà (1992) asked whether volleyball athletes display superior spatial orienting skills in comparison to nonathletic participants. Participants performed the Posner cueing task (Posner et al., 1980), where they made a speeded key press when a visual target appeared in one of several possible locations. Prior to the target, a centrally located visual arrow indicated the probable target location. Castiello and Umiltà (1992) found that both groups performed comparably when the arrow correctly predicted the target location. That is, volleyball players showed no unique advantage in initial orienting ability when responding to predictive symbolic information. However, when the arrow falsely indicated the target location, volleyball players were faster to identify the target than nonathletes. They concluded that volleyball players were faster to reorient attention than nonathletes when presented with misleading information.

Lum et al. (2002) followed up this research by comparing the spatial orienting skills of athletes from multiple sports. They compared university athletes from two static sports (swimming and track teams), two dynamic sports (volleyball and soccer teams), and nonathletes on two different types of visual cues in a Posner cueing task: a brief flash at one of the potential target locations designed to pull attention by triggering a spatial orienting reflex, and a central arrow cue designed to indicate where participants should push their attention because it indicated a highly probable target location. All participants responded faster, as expected, when either the arrow or the flash correctly predicted the target location. However, the novel finding was that dynamic and static sport athletes showed differential effectiveness of these two cues based on how much time had passed between cue and target appearance. Specifically, when both the flash and arrow correctly predicted the target location, and the target appeared within 100 milliseconds of the flash, static sports athletes performed fastest. However, when this time interval was increased to 405 or 795 milliseconds, athletes from dynamic sports were now the quickest. This latter result suggested that athletes from dynamic sports were more adept in shifting attention back toward a previously cued target location, whereas static sport athletes having already directed attention to this location, were less likely to return to it in the near future. This implied reduced attentional flexibility in spatial orienting among static sport athletes.

Lum et al. (2002) interpreted these findings in light of the training differences that characterize these two sport-types. For example, static sports athletes are accustomed to anticipating a starting signal while at the same time ignoring other distracting information (e.g., spectators and other athletes). Dynamic sports athletes, by way of contrast, must often remain flexible and prepared to quickly shift attention from one spatial location to another, either among various teammates they are cooperating with and/or among opponents they are competing against. In ice hockey, for example, the environment is fast-paced, with the puck being passed rapidly from player to player and team possession of the

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puck having the potential to suddenly switch. The average shift duration within the National Hockey League is also 40-50 seconds, meaning that for these professional athletes' attention must be mobile and highly flexible under brief and intense periods of play (Montgomery et al., 2004). All this suggests that in mastering their sport, athletes from dynamic sports are required to refine their spatial orienting abilities in order to be attentionally flexible.

*Attention shifting and tracking*

What does it mean to shift and track attention from one location to the next? Doing so effectively is critical for athletes deciding what actions to take next. Williams et al. (1994) studied this process by asking experienced and inexperienced soccer players to view footage of soccer play while their eyes were being tracked. In each recorded vignette, the last player to have possession of the ball was highlighted, before participants made speeded reports of where they thought the next pass would be made. All players were comparably accurate, but experienced players responded more rapidly than inexperienced players. Experienced players also adopted a more explorative strategy than inexperienced players, making a greater number of fixations, of shorter duration, and more often toward the position and movement of other players.

Williams et al. (1994) interpreted these findings as supporting sports-specific tuning of attention skills (see also Vater et al., 2020). Rapid exploratory search is likely to be adaptive when faced with multiple opponents in the field. When there are none, or only one relevant opponent, a narrower and more focused attentional strategy is better suited to the situation. This point was supported by Savelsbergh et al. (2002), who asked expert and nonexpert soccer goalkeepers to view footage of penalty kicks and to adjust a joystick in order to block the anticipated shot. Both groups of goalkeepers performed comparably on gross measures (e.g., blocking the shot) but the expert goalkeepers were more accurate in the finer details (e.g., adjusting to the ball height) and made fewer corrective movements. Their eye fixations were also fewer in number, with longer fixation times, and greater spatial concentration relative to nonexpert goalkeepers.

The ability to shift attention in space has also been studied in the lab with the trail making test. Two common variants are trail making test A and trail making test B. In test A participants connect randomly dispersed numbers on a page (i.e. 1-2-3-4) and in test B they connect numbers and letters in alternating order (i.e. 1-A-2-B-3-C). Time to complete test A is taken as a measure of visual search (scan-identify-scan again), and time to complete test B is taken as search with an additional shift operation (scan-identify-shift-scan again). Higher-skilled athletes have been found to be faster than lesser-skilled athletes on these measures. For example, Han et al. (2011) reported that trail making A times did not differ with skill among soccer and baseball players, however more skilled players were faster to complete trail making B than lesser-skilled players. Huijgen et al.

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(2015) also reported that elite youth soccer players had greater attentional shifting than nonelite players, here measured by subtracting completion time for trail making B by trail making A. Marsh et al. (2010) further reported that time to complete time trail making B correlated with the accuracy of shots on target by college lacrosse players.

One reason why an athlete may shift attention from one location to another is to recognize specific spatial-temporal patterns in their own teammates as well as those of the opposing team. In soccer, for instance, players adopt formations that are tailored to specific situations, making some forms of gameplay more likely than others. A common formation that favors balanced offensive and defensive play is 4-4-2, in which 4 players act as defenders, 4 as midfielders and 2 as forwards. Other formations are biased more toward offensive (e.g. 3-4-3) or defensive (e.g. 4-5-1) play. Several studies suggest that the ability to quickly recognize such patterns distinguishes highly-skilled from lesser-skilled athletes (Abernethy et al., 2005). Williams et al. (2006), for instance, tested whether semi-professional soccer players had superior pattern recognition skills than recreational players, by having them view footage of soccer game sequences. Players were subsequently tested with a new-old recognition task in which familiar sequences had to be discriminated from novel ones. Although both groups had comparable accuracy in identifying a sequence as new or old, semi-professional soccer players were faster to do so. A follow up study had participants complete a new-old recognition test after viewing soccer sequences depicted only as point-light displays. These displays retain the relational properties among soccer players while removing all non-motion features (e.g., color, shape, identity). When only this information was available, semi-professional soccer players were both faster and more accurate than recreational soccer players.

Information collected through serial shifts of attention can help an athlete maintain awareness of teammate and opponent locations. A hockey player for instance can use such information to anticipate where and when a pass is most likely to be made amongst opposing players. The ability to track and monitor multiple entities within a visual environment has been studied using various multiple object tracking tasks. Zhang et al. (2009) as an example showed university volleyball players and students displays of identical letters (the letter "B") dispersed across locations on a computer screen. A subset of these letters would then briefly flash, designating them as targets to be tracked for that given trial. All the letters then began moving randomly, with some of them also changing color. At the end of the trial, all letters transformed into the letter "H", except for one of the previously denoted target letters that transformed into a "p" or "q". Participants were required to discriminate this unique letter as quickly and accurately as possible. Volleyball players completed this task with greater speed than university students, while retaining comparable accuracy. These results thereby suggesting faster tracking ability amongst volleyball athletes.

Multiple object tracking tasks have also been found to differentiate expertise among athletes of the same sport. Qiu et al. (2018) for instance

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tested nonathletes, intermediate and elite basketball players on a multiple object tracking task. No group differences were found when there were only 2 target stimuli to track. However, elite basketball players showed greater tracking accuracy than intermediate players and nonathletes as the number of targets increased. Faubert (2013) also tested professional athletes in a variety of sports (soccer, hockey, and rugby), as well as elite amateurs and nonathletes on a multiple object tracking task over repeated sessions. Professional athletes were superior to elite amateurs and nonathletes on this task during the first session, and also showed a steeper rate of improvement as sessions continued. Elite amateurs on the other hand were only able to separate themselves from nonathletes after multiple sessions of this task had been completed.

### *Attentional breadth*

Does the functional use of peripheral vision vary between athletes and nonathletes? Situational awareness in a sporting environment is often dependent on one's attentional breadth. An athlete who is monitoring the position of teammates in their visual periphery can act sooner than an athlete who must deliberately shift their attention in order to recognize these same teammates. Visual perimetry tasks were among the earliest measures used to study the attentional breadth of athletes. In some versions of this task, participants sit in front of a large screen and report when they detect a peripheral dot advancing toward the center of gaze. Attentional breadth is then measured by the average distance from the center that target dots can be detected for a given threshold level of accuracy.

Williams and Thirer (1975) tested nonathletes and athletes from a variety of sports on a perimetry task. They reported that athletes generally detected targets over a wider horizontal and vertical distance relative to nonathletes, and females appeared to detect targets over a greater vertical span than did males. A follow-up study by Berg and Killian (1995) reported that female softball players showed wider attentional breadth than female nonathletes on a perimetry test, though individual differences in seasonal batting averages and pitching-machine batting tests for the athletes did not correlate with the perimetry task.

More recent studies of attentional breadth in sports have employed the useful field of view task, where participants must detect stationary peripheral targets that appear in varying distances from a central location, often among distractors. For example, Murphy (2017) compared golfers with aerobically fit non-golfers on this task in order to test the hypothesis that golf promotes wider attentional breadth. Golfers were overall more accurate in detecting targets across all distances than were non-golfers, implicating effective visual performance over a larger attentional breadth (Ball & Owsley, 1993).

Some studies suggest that certain sports modify an athlete's attentional breadth in accordance with the sport's environmental demands. For example, soccer and hockey emphasize shifting attention along a

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predominantly horizontal plane, while volleyball and basketball demand precise attentional control over the vertical plane as well. Hüttermann et al. (2014) tested whether the attentional breadth of athletes varied in these predictable ways.

Their measure of attentional breadth was a task involving brief presentations of intermixed circles and triangles on a computer screen, in varying shades of grey. These shapes appeared in clusters with one another, and participants were required to make numerosity estimates of some of the shapes (e.g. estimate the number of light triangles) across trials where these clusters varied in their spatial distances from one another and their location from center gaze. A performance threshold of 75% accuracy was determined for each participant, in each of the combinations of cluster distance and location. In general, athletes who had been training longer had larger attentional breadth than those with less training. Sports-specific effects were also reported. Handball and soccer athletes had wider attentional breadth along the horizontal plane, and volleyball and basketball athletes had wider attentional breadth over the vertical plane. Scharfen and Memmert (2019) also used this same task to show that a larger breadth over the diagonal plane correlated with dribbling performance in elite youth soccer players.

### *Attentional control*

What is needed to manage the push and pull tendencies of visual attention? Consider the case of a hockey goaltender who must be alert to the possibility that an opposing player with the puck may be extending their body in order to execute a slapshot, but they may also be doing so in order to conceal a pass to a teammate in another location. In this scenario, the goaltender may be required to inhibit an automatic or habitual perceptual interpretation in order not to be deceived by the opposing player. Attentional control, which involves executing the correct mix of inhibitory and excitatory processes in a given situation, is commonly studied in the lab using the Stroop task, the flanker task, the stop-signal task, and the quiet-eye phenomenon.

The Stroop task is among the most popular measures in all of behavioral research (MacLeod, 1991). There are many variants of the Stroop task, but the key ingredients are that participants are asked to identify one feature of a stimulus while ignoring other features of that stimulus that may impede identification because of reflexive or habitual responding. Performing this task optimally requires control over the push (goal-directed intentions) and pull (reflexes or habits) demands inherent in the task. For example, in a color-naming Stroop task, participants are asked to name the ink-color of a printed word (e.g., blue), and the word itself may spell a congruent color name (e.g. "blue") or incongruent name (e.g. "red"). There is a pull of attention to read the printed word because of overlearned reading habits, but the imperative task is to push attention to identify the ink-color of the printed letters. The speed and accuracy with

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which colors are named on incongruent trials versus congruent trials is then commonly taken as an index of attentional control.

Jacobson and Matthaeus (2014) tested athletes of various sports and at varying skill levels, as well as nonathletes, on the Stroop task. They reported that athletes generally showed greater attentional control on the Stroop task, and that athletes from self-paced sports (e.g., swimming and cross-country runners) performed especially well. The authors interpreted these results as reflecting the influence of sport-specific environmental demands on improved attentional control. They reasoned that a swimmer or a cross-country runner must successfully inhibit the pull to stop competing, especially when exhausted or experiencing internal pain. This reliance on the self to push attention in the service of one's goals may help reinforce a mindset that improves inhibitory control over pull tendencies.

Sakamoto et al. (2018) tested soccer players aged 8-11 years on a Stroop task during their evaluation for an elite youth soccer program. Although admission to the program was based solely on soccer skill assessment, admitted players tended to have greater attentional control on a timed version of the Stroop task than players who were rejected. In their interpretation, the authors considered both the possibility that improved attentional control may be a contributing factor to sports success, as well as the possibility that sports participation contributes to the refinement of attentional control.

The flanker task provides a measure of attentional control in the spatial domain. Participants are asked to identify a centrally positioned target in an array (the push) as rapidly as possible, and the remainder of the array consists of distractor items that pull attention because they depict stimulus-response mappings that are either congruent with the central target or are incongruent. For example, a participant may be asked to indicate the direction of a central arrow with a spatially-mapped key press (e.g. pushing the left key for a left-pointing arrow) and this central arrow is flanked by arrows that are pointing in the opposite direction (e.g, the pull to the right must be inhabited). A *flanker effect* is then often calculated and is the difference in response time and accuracy between incongruent and congruent trials, and is interpreted as a measure of attentional control over visual space.

Chiu et al. (2017) reported that athletes from static sports (runners and swimmers) had comparable flanker task accuracy to nonathletes, whereas athletes from dynamic sports (volleyball) were more accurate than nonathletes. Krenn et al. (2018) further separated athletes into one of three categories: static sports (e.g. swimming, weight lighting), dynamic coordination and interceptive sports, (e.g. alpine skiing, mountain biking sports), and strategic sports where athletes must adapt to quickly changing environmental circumstances (e.g. volleyball, hockey). Although all athletes had comparable flanker task accuracy, athletes from sports with less predictable environments (strategic sports) had faster response times on both congruent and incongruent trials.

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Wylie et al. (2018) reported that university football players, in addition to having generally smaller flanker effects than nonathletes, had different sized flanker effects, depending on their role. Defensive players (i.e. linemen, linebackers, and backs) had smaller flanker effects than nonathletes, implicating greater attentional control, whereas among offensive players, only wide receivers and tight ends (not quarterbacks, running backs or offensive linemen) showed this same advantage over nonathletes. These results imply that the players most responsible for detecting deception in the actions of opposing players also have the greatest attentional control.

Once an athlete has failed to correctly predict the action of an opponent, or has been deceived by them, they must quickly reset their goals. Consider again the hockey goaltender who is prepared to block a slapshot when instead a pass is made. Once the goaltender detects this change in circumstance, they must stop an action that has been prepared (blocking) and instead engage the appropriate defensive action (track the pass). Attentional control that involves explicit action cancellation has been studied in athletes using the stop-signal task. On most trials of a typical stop-signal task, a target must be acted on (e.g. a circle presented on the left or right side of a computer screen requires pressing the spatially corresponding key), and on a minority of trials a secondary stimulus appears (e.g. a central circle). This secondary stimulus indicates that all previously planned responses must be immediately stopped, and that any response past this point would be indicative of failed action cancellation. Experiments typically vary the temporal lag between the go and stop stimuli until a threshold level of accuracy is achieved (e.g. 50%). This threshold temporal lag value is then used (and potentially slightly shifted) to estimate a response time measure of inhibitory control called the stop-signal reaction time.

Wang et al. (2013) reported that dynamic sport athletes (tennis players) had a faster stop-signal reaction time than static sport athletes (swimmers) and nonathletes. They interpreted this finding in support of greater environmental-tuning of inhibitory control among tennis players. Other studies have reported differential stop-signal effects for players of the same sport based on their skill level. For example, Huijgen et al. (2015) reported that elite youth soccer players had faster stop-signal reaction time than sub-elite players. Heppe and Zentgraf (2019) further asked whether stop-signal reaction time among athletes is linked to bodily actions characteristic of their sport. They tested handball experts and recreational athletes in a stop-signal task using either a hand or a foot response. Handball experts showed significantly faster stop-signal reaction times compared to recreational athletes, but this effect held only for hand responses, and not for those made with the feet.

A few studies have tested both the flanker task and the stop-signal task in the same groups of athletes, and have reported differential effects. For example, Verburgh et al. (2014; 2016) tested expert and novice soccer players on both tasks and found that more skilled players showed greater attentional control than less skilled players only on the

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stop-signal task. The author's interpretation was that the flanker task involves the resolution of conflicting information at a perceptual stage of processing, whereas the stop-signal task measures the ability to stop an already prepared action. Other researchers have made similar distinctions between these two tasks (e.g. Chu et al., 2015; van Velzen et al., 2014). This distinction may thus suggest that some sports differentially train one form of attentional control over another.

Another widely studied measure of attentional control in the visual domain concerns the quiet-eye phenomenon (Vickers, 2016). The quiet-eye interval refers to the time that elapses from the final fixation on a spatial target (e.g. front of a hoop) before the initiation of a motor sequence (e.g. throwing a basketball). This interval is specifically relevant to sports requiring target-eye coordination, where many studies have shown that longer quiet-eye intervals are associated with more accurate motor movements. The quiet-eye is thought to involve attentional control because the eyes have a natural tendency to be exploring the visual field for new information. A large body of literature has accumulated showing that more skilled athletes tend to have longer quiet-eye intervals than less skilled athletes (Vickers, 2016). For example, when elite basketball players execute a free throw, they fixate sooner on the front of the hoop and hold this fixation for a longer period of time before initiating a shot than do nonexperts (Vickers, 1996). Before initiating a strike, skilled golfers also maintain fixation on the back of a golf ball for a longer period of time than do less skilled golfers (Vickers, 1992). When hockey goaltenders successfully block a shot, they too fixate earlier and longer on the hockey puck than when they fail to block a shot (Panchuk & Vickers, 2006).

Attentional control has also been reported to improve following brief bouts of exercise. A study by Chen et al. (2014) had preadolescent children complete a flanker task before and after either a 30-minute period of jogging or reading. No baseline differences were found in these two groups, but the children who exercised went on to show greater attentional control compared to children who read as indicated by a smaller response time difference between incongruent and congruent trials. A session of basketball has also been reported to benefit attentional control on the flanker task among adolescents (Spitzer & Furtner, 2016), and among young adults exercise has been reported to reduce response time for both congruent and incongruent trials (Ludyga et al., 2018), as well as lessen the reaction time difference between incongruent and congruent trials (O'Leary et al., 2011). These results are further complimented by studies showing that jogging on a treadmill (Chu et al., 2015) and cycling (Joyce et al., 2009), compared to passive control conditions, yield faster stop-signal reaction times.

Some research points to dose-effects, meaning that the intensity of exercise is associated with cognitive benefits (Aks, 1998). Kamijo et al. (2009) had young and old adults complete a flanker task before and after cycling at 30% or 50% of their VO.max (determined by a prior graded cycling test). Moderate exercise resulted in faster response times, with

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no sacrifice in accuracy, compared to light exercise. A result favoring high-intensity exercise was also obtained by Gejl et al. (2018), who had adolescents complete a flanker task after resting, or after cycling for five minutes at 50%, 65% or 80% of their maximal oxygen uptake reserve. They found that accuracy improved regardless of exercise intensity, but response times only improved following the most intense (80%) exercise condition.

There is very little research on the relationship between exercise and attentional breadth, but of the research available, higher intensity exercise again appears more beneficial. For example, Roth et al. (2003) had older adults report their typical frequency (times per week), duration (in minutes), and intensity (low, moderate or high) of different exercises they participate in (e.g. running) before completing a useful field of view task. More frequent and higher intensity exercise were both found to correlate with greater attentional breadth. Ando et al. (2017) also asked elderly participants to complete a useful field of view task after wearing accelerometers for 3-6 days. Metabolic equivalents (METS) were then used to categorize participant activity during this period into sedentary behavior (≤ 1.5 METs), light physical activity (1.6-2.9 METs), moderate physical activity (3.0-5.9 METs), and vigorous physical activity (≥ 6.0 METs). The researchers found that after adjusting for age and device wear time, more time spent in vigorous physical activity correlated with a more efficient useful field of view.

Complicating the interpretation of these results are other studies showing that higher intensity exercise is not uniformly superior. For instance, a study with older women found that self-reported moderate intensity, but not high-intensity, physical activity associated with faster trail making B performance (Tierney et al., 2010). One hypothesis is that for exercise to be optimally beneficial, intensity must be matched with baseline fitness. A relevant study here comes from Hüttermann and Memmert (2014), who had athletes and nonathletes exercise at 50%, 60%, or 70% of their maximum heart rate while completing an attentional breadth task. Athletes as a group displayed greater attentional breadth, but there were also distinguishable positive effects of exercise intensity. For athletes, the relationship was linear with their best performance coinciding with the 70% intensity level. For nonathletes, on the other hand, performance peaked at 60%, with reduced task performance at both lower and higher levels of exercise intensity.

Complicating the picture even further are several reports of null findings. Ho et al. (2018) for instance asked university students to self-report their physical activity over the past week before completing a flanker task. They were unable to find any correlation between physical activity, regardless of intensity, and flanker task performance. Another study by Loprinzi and Kane (2015) had young adults complete trail making A and B following a control condition or a 30-minute treadmill exercise set to 40-50%, 51-70%, or 71-85% of their maximal heartrate. Regardless of intensity level, exercise again was not found to aid performance on either trail making task. A longitudinal study by

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Marmeleira et al. (2009) also had older adults complete trial making B before and after assignment to a 12-week exercise or control condition and here too no difference was found between the groups on study completion.

Although pairing individual fitness levels with exercise intensity may elucidate the relationship between exercise and attention, there are likely other factors that also underlie reported null findings and inconsistencies in the literature. These include differences in exercise duration (e.g. number of minutes), adherence (e.g. frequency), social interactivity (e.g. alone or with others), and cognitive engagement. Cognitive engagement is itself a broad term that may reflect simple differences between exercise activities, like whether one has to keep a running mental clock or whether timing matters within one's exercise (e.g. jogging for leisure versus training for a specific marathon time). Some have hypothesized that more complex exercise, and in particular exercise that relies on executive functioning (e.g. inhibitory control) is the most beneficial and likely to produce cognitive benefits (Best, 2010; Diamond & Ling, 2016).

*Attention training and sport performance*

Do the links between measures of attention and sport performance reviewed in the previous subsections imply that attention training programs in the lab are of benefit to athletic performances on the field? Perhaps the most convincing case for this comes through research on the quiet-eye (see review by Vickers, 2016). For instance, Harle and Vickers (2001) assigned one team of varsity basketball players to complete quiet-eye training while two other teams did not. The team that received quiet-eye training went on to show greater free throw accuracy in a laboratory setting, and in the following competitive season achieved a higher overall free throw accuracy. Other studies also report that simply participating in sports-specific training (e.g., golf) can result in a longer quiet-eye interval, even when the quiet-eye effect is itself not an explicit part of the training (Vine & Wilson, 2010).

Research by Romeas et al. (2016) found that multiple object tracking was beneficial for sport performance. Here soccer players were assigned to either a 5-week multiple object tracking schedule, a schedule of viewing soccer footage, or a control group. At study completion the tracking group had higher passing accuracy, as well as higher self-ratings of decision-making confidence than the other two groups. More general training regimes in visual, perceptual, and cognitive skills have also sometimes been reported to improve athletic performance (for a review see Appelbaum & Erickson, 2018).

We hasten to add that not all attention training programs have been found to be beneficial (e.g. Abernethy & Wood, 2001) and others caution that substantially more research is needed before more definitive or substantial claims about training are warranted (e.g. Walton et al., 2018). It is also worth noting that not all studies find an association between attention and sport. A study by Memmert et al. (2009) for instance had

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athletes from three categories (handball, non-team sports, and novice athletes) complete three laboratory measures of attention (useful field of view task, multiple object tracking task, and an inattentional blindness task). Not only were there no significant differences on these tasks between the three groups of participants, but performance on the three attentional tasks were largely uncorrelated with one another. Findings such as these should temper both theoretical accounts of attention and the promotion of attention-based training regimes for athletes.

*Working memory and sports*

Do the attention tasks we have reviewed exhaust the cognitive constructs relevant to sport performance? The answer is an unequivocal no. We have simply limited our review to a handful of the most popular measures of visual attention. This does not diminish the importance of many other cognitive constructs. One worth mentioning briefly is working memory. Working memory refers to the ability to mentally represent, store, and manipulate a small number of items that are relevant to an ongoing task, but may no longer be in view. Individuals differ quite reliably from one another in the estimated capacity of their working memory, which can range in any given test from only 1-2 items to 5-7 items. So although working memory is not in a strict sense visual, it is nonetheless critically involved in many of the attention tasks we have reviewed, including Stroop (Long & Prat, 2002; Meier & Kane, 2013), flanker (Heitz & Engle, 2007; Pratt et al., 2011), trail making (Crowe, 1998; Sánchez-Cubillo et al., 2009), and visual search tasks (Awh et al., 2006; Han & Kim, 2004). In each of these tasks, some critical information must be represented in working memory in order to perform well (e.g., the instructions with regard to stimulus response mappings, possible targets to monitor, which of the many features of a target are relevant and worth responding to). It is clear to us from even a cursory search for research articles testing working memory in various sports contexts that this is a burgeoning field of interest (see Furley & Memmert, 2010).

There are studies, for instance, linking the tactical decisions made by athletes to their working memory capacity. In one study, Furley and Memmert (2012) asked basketball players to view still images taken from a basketball game and to decide whether the optimal strategy for the player with the ball was to shoot, dribble or pass. Distracting auditory information was presented along with these visual images. The results showed that basketball players with higher working memory capacities (measured prior via a counting span task) selected the optimal play more often, and were less likely to notice their name being pronounced within the distracting auditory information. In a second study, hockey players viewed still images of hockey games and made decisions about what the optimal play was for the player with the puck. In advance of some trials, they would hear advice from a virtual coach, and most, but not all of the time, this advice was helpful in determining the optimal play. Hockey players with smaller working memory capacity were overly reliant on this

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advice and made poorer choices when it was not applicable. Conversely players with larger working memory capacity were more readily capable of adapting as gameplay progressed.

*A note on reliability and validity*

It is fair to say that the literature on laboratory measures of attention has historically paid little attention to the psychometric notions of reliability and validity. This issue has been highlighted recently by several researchers (e.g., Goodhew, 2020; Hedge et al., 2018). Some of this neglect can be attributed to different research traditions. Typical laboratory studies focus on within-participant designs in order to isolate a difference between two different cognitive processes or to measure the consequence of adding to the load of a single cognitive process. Reliability in this context refers to the probability of obtaining the same result with an independent sample of participants. We can call this a group effect. When a group effect is replicated numerous times, in a variety of contexts, by different author groups, it comes to be seen as reliable. The question of the validity of a group effect therefore concerns whether the measured group effect is predictive of the group's performance on a theoretically-related task. We have seen many examples of this kind of research in the previous subsections, where the hypothesis being tested is whether one's status as an athlete (e.g., between novice and elite athletes) translates into a group difference on an attention task. Finding such a difference that favors the elite athletes is thus some validation for the attention construct behind the laboratory task. There are numerous examples of this in the literature summarized in Table 1.

The research strategy of a typical psychometric study, on the other hand, focuses on the degree to which a measurement made on an individual is stable from one occasion to the next. Reliability in this context refers to test-retest reliability at the individual level and validity refers to whether these individual differences correlate well with other theoretically-relevant measures at the individual level. We can call these individual effects. It is safe to say that there has been very little exploration of individual effects in the laboratory attention literature to date. However, this is now beginning to change (Goodhew, 2020).

To complicate matters even further, Hedge et al. (2018) note that the research goals of group studies and studies of individual differences are fundamentally opposed to one another. Factors that serve to increase the statistical reliability of group effects are in direct opposition to factors that increase the statistical reliability of individual effects. This is because finding stable group differences is premised on there being relatively little individual variability in the measured effect, whereas stable individual differences are premised on there being large individual variability. The increased reliability of group effects thus comes at the expense of reliability at the individual level, and vice versa.

In the next section we will encounter a larger number of studies that focus on individual differences. As we encounter them, it will be

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important to bear in mind that the concepts of reliability and validity have these different interpretations in the literature we have reviewed in section 2 (group studies) and are about to encounter in section 3 (individual differences studies).

## Factors influencing athletics and attention in the field

In this section we turn to real-world factors that influence both athletic success on the field and performance on laboratory measures of attention. Our search for these factors was inspired by our parallel reading of the sports and attention literatures. In the cognitive science literature, there has been a recent paradigm shift that emphasizes the importance of studying attention with real-world stimuli and in naturalistic settings (Kingstone et al., 2003; Ristic & Enns, 2015b). In our mind, this emphasis aligns well with the sports literature, which has always had a real-world focus. Note that the findings reviewed in this section come from literatures that have not referenced one another very often in the past. Yet we find the conceptual parallels in these two literatures to be inescapable and therefore of importance to understanding the connection between athletics and attention.

We determined the entries in Table 2 by combining several criteria, including that a paper had to reference one of the attention tasks we reviewed in the previous section and that a paper had to reference one of the specific terms we grouped into behavioral practices, environmental conditions or individual differences. These terms emerged both from the factors that attention theorists are now considering to be important for understanding attention (see section 4) and from their relative popularity as factors to be considered in the sports literature. As in the previous section, these terms should be taken as representative, but not exhaustive, of a larger body of literature. The values in Table 2 therefore represent the frequency with which peer-reviewed articles were found in August 2020, using *Web of Science*, that refer both to the real-world factors we review and of the attention tasks we have already discussed.

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**Table 2**

The frequency of articles reported by Web of Science to contain the conjunctions of behavioral, environmental, and individual difference factors, with attention measures, in the titles, abstract and keywords. Attention measures are grouped into constructs that form the basis of many theoretical frameworks for attention. The search was conducted in August 2020, using the advanced search function in the Web of Science Core Collection, for English-language peer-reviewed articles in the period 1920-2020.

| Factor | Orienting | Shifting & tracking | | | Breadth | | Attentional control | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Behavioral** | Posner or spatial cueing | Visual search | Trail making | Multiple object tracking | Useful field of view | Perimetry | Stroop | Flanker | Stop signal | Quiet-eye | |
| **Exercise/fitness** | 19 | 447 | 14 | 11 | 44 | 25 | 616 | 126 | 23 | 10 | 1335 |
| **Sleep** | 19 | 185 | 9 | 2 | 6 | 31 | 256 | 21 | 10 | 0 | 539 |
| **Hydration** | 1 | 6 | 0 | 0 | 0 | 0 | 9 | 2 | 0 | 0 | 18 |
| **Environmental** | | | | | | | | | | | |
| **Competition** | 43 | 722 | 0 | 33 | 1 | 4 | 233 | 62 | 13 | 17 | 1128 |
| **Distraction** | 25 | 367 | 1 | 16 | 9 | 3 | 172 | 40 | 11 | 5 | 649 |
| **Thermal stress** | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 3 |
| **Individual** | | | | | | | | | | | |
| **Age** | 191 | 2840 | 102 | 57 | 184 | 1880 | 2693 | 323 | 247 | 7 | 8524 |
| **Gender, Sex** | 83 | 626 | 32 | 18 | 29 | 234 | 965 | 72 | 123 | 1 | 2183 |
| **Personality** | 23 | 115 | 8 | 2 | 1 | 1 | 356 | 49 | 98 | 0 | 653 |

### *Behavioral practices*

#### *Exercise*

It is no surprise that athletes generally exercise more than nonathletes. Sorenson et al. (2015) documented that intercollegiate athletes, when compared to nonathletes, reported greater amounts of exercise in their daily lives, were more likely to rate exercise as important, and were more likely to meet recommended exercise guidelines. In the cognitive science literature, engaging in exercise has also been reported to benefit attentional shifting. For instance, Benedict et al. (2013) asked older adults to report how frequently they engaged in various forms of exercise and physical activity (e.g. swimming, running) for at least 30 minutes in the course of a week. Participants who exercised more frequently were also those with faster trail making B completion times. Studies using more objective measures of physical exercise have provided similar results. Barnes et al. (2008) studied older women wearing accelerometers over 2-5 days and found that participants who moved the most during the daytime also tended to have the fastest trail making B completion times.

Even brief bouts of exercise have been found to benefit attentional shifting among young adults. Murray and Russoniello (2012) had young adults complete trail making B before and after assignment to an exercise or control condition. Exercise here consisted of pedaling a stationary bicycle for 30 minutes. Participants showed faster completion times

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overall from one testing session to the next, but participants who exercised were significantly faster than those who did not. Similar results were reported by Harveson et al. (2016), who found that trail making B performance improved among high school students following 30 minutes of walking and jogging, but not after resistance training or a no-exercise control condition.

Adherence to exercise has also been reported to benefit attentional control. Studies using self-report measures have found that older adults who exercise regularly respond more quickly on a flanker task (Huang et al., 2014), and that young adults who exercise regularly show less interference from flankers (Pérez et al., 2014). Padilla et al. (2013; 2014) reported similar results showing that participants who reported regularly exercising had faster stop-signal reaction times compared to non-exercising participants on a strategic version of the stop-signal task.

Attentional control has also been reported to improve following brief bouts of exercise. A study by Chen et al. (2014) had preadolescent children complete a flanker task before and after either a 30-minute period of jogging or reading. No baseline differences were found in these two groups, but the children who exercised went on to show greater attentional control compared to children who read as indicated by a smaller response time difference between incongruent and congruent trials. A session of basketball has also been reported to benefit attentional control on the flanker task among adolescents (Spitzer & Furtner, 2016), and among young adults exercise has been reported to reduce response time for both congruent and incongruent trials (Ludyga et al., 2018), as well as lessen the reaction time difference between incongruent and congruent trials (O'Leary et al., 2011). These results are further complimented by studies showing that jogging on a treadmill (Chu et al., 2015) and cycling (Joyce et al., 2009), compared to passive control conditions, yield faster stop-signal reaction times.

Some research points to dose-effects, meaning that the intensity of exercise is associated with cognitive benefits (Aks, 1998). Kamijo et al. (2009) had young and old adults complete a flanker task before and after cycling at 30% or 50% of their VO2max (determined by a prior graded cycling test). Moderate exercise resulted in faster response times, with no sacrifice in accuracy, compared to light exercise. A result favoring high-intensity exercise was also obtained by Gejl et al. (2018), who had adolescents complete a flanker task after resting, or after cycling for five minutes at 50%, 65% or 80% of their maximal oxygen uptake reserve. They found that accuracy improved regardless of exercise intensity, but response times only improved following the most intense (80%) exercise condition.

There is very little research on the relationship between exercise and attentional breadth, but of the research available, higher intensity exercise again appears more beneficial. For example, Roth et al. (2003) had older adults report their typical frequency (times per week), duration (in minutes), and intensity (low, moderate or high) of different exercises they participate in (e.g. running) before completing a useful field of view

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task. More frequent and higher intensity exercise were both found to correlate with greater attentional breadth. Ando et al. (2017) also asked elderly participants to complete a useful field of view task after wearing accelerometers for 3-6 days. Metabolic equivalents (METS) were then used to categorize participant activity during this period into sedentary behavior (≤ 1.5 METs), light physical activity (1.6-2.9 METs), moderate physical activity (3.0-5.9 METs), and vigorous physical activity (≥ 6.0 METs). The researchers found that after adjusting for age and device wear time, more time spent in vigorous physical activity correlated with a more efficient useful field of view.

Complicating the interpretation of these results are other studies showing that higher intensity exercise is not uniformly superior. For instance, a study with older women found that self-reported moderate intensity, but not high-intensity, physical activity associated with faster trail making B performance (Tierney et al., 2010). One hypothesis is that for exercise to be optimally beneficial, intensity must be matched with baseline fitness. A relevant study here comes from Hüttermann and Memmert (2014), who had athletes and nonathletes exercise at 50%, 60%, or 70% of their maximum heart rate while completing an attentional breadth task. Athletes as a group displayed greater attentional breadth, but there were also distinguishable positive effects of exercise intensity. For athletes, the relationship was linear with their best performance coinciding with the 70% intensity level. For nonathletes, on the other hand, performance peaked at 60%, with reduced task performance at both lower and higher levels of exercise intensity.

Complicating the picture even further are several reports of null findings. Ho et al. (2018) for instance asked university students to self-report their physical activity over the past week before completing a flanker task. They were unable to find any correlation between physical activity, regardless of intensity, and flanker task performance. Another study by Loprinzi and Kane (2015) had young adults complete trail making A and B following a control condition or a 30-minute treadmill exercise set to 40-50%, 51-70%, or 71-85% of their maximal heartrate. Regardless of intensity level, exercise again was not found to aid performance on either trail making task. A longitudinal study by Marmeleira et al. (2009) also had older adults complete trial making B before and after assignment to a 12-week exercise or control condition and here too no difference was found between the groups on study completion.

Although pairing individual fitness levels with exercise intensity may elucidate the relationship between exercise and attention, there are likely other factors that also underlie reported null findings and inconsistencies in the literature. These include differences in exercise duration (e.g. number of minutes), adherence (e.g. frequency), social interactivity (e.g. alone or with others), and cognitive engagement. Cognitive engagement is itself a broad term that may reflect simple differences between exercise activities, like whether one has to keep a running mental clock or whether timing matters within one's exercise (e.g. jogging for leisure

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versus training for a specific marathon time). Some have hypothesized that more complex exercise, and in particular exercise that relies on executive functioning (e.g. inhibitory control) is the most beneficial and likely to produce cognitive benefits (Best, 2010; Diamond & Ling, 2016).

*Sleep*

Sleep is important for general bodily functioning and has sports-specific benefits. Mah et al. (2011) monitored basketball players for a 2-4 week baseline period, after which athletes were instructed to increase their total sleep duration to a goal of at least 10 hours per night for 5-7 weeks. During this period athletes slept on average about two hours longer than in the baseline period (as measured by self-report and actigraphy data). Athletic testing further revealed participants had faster sprint times, as well as more accurate free throwing and three-point field goals. Schwartz and Simon (2015) completed a similar study in which tennis players increased their sleep duration by approximately 2 hours more per night, during which time they also improved their tennis serve accuracy.

Although studies suggest sleep is important for sport performance, athletes often experience reduced quantity as well as quality of sleep for a variety of reasons (Halson, 2014; O'Donnell et al., 2018; Simpson et al., 2017). Leeder et al. (2012) measured sleep, using wristwatch actigraphy, in Olympic athletes from various sports (i.e. canoeing, diving, rowing, and speed skating) and nonathletic controls. They found that although athletes spent more time in bed, they did not spend more time asleep. Rather athletes needed more time to fall asleep, were more restless, spent more time moving, and had lower sleep efficiency. Such sleep loss can in turn have detrimental effects on sport performance, including lesser aerobic endurance (Oliver et al., 2009), quicker physical exhaustion (Martin, 1981), slower sprint times (Skein et al., 2011). reduced tennis serve accuracy (Reyner & Horne, 2013), and worse performance on a soccer continuous kicking test (Pallesen et al., 2017).

The literature documenting impaired sport performance from sleep loss is in agreement with literature showing that sleep loss impairs attention. Wimmer et al. (1992) had undergraduate students complete trial making B before and after one group was permitted to sleep through the night while the other group was not. In the post-test, both groups were faster than the pre-test, reflecting practice related improvement. However, difference scores revealed that sleep-deprived participants were significantly slower relative to non-deprived participants. Less extreme sleep problems such as requiring more time to fall asleep (Blackwell et al., 2006), and reduced sleep quality (Nebes et al., 2009), have each also been found to associate with worse trail making B performance.

Sleep-deprived individuals are also slower, more variable, and less accurate when completing a flanker task (Tsai et al., 2005), show slower stop-signal reaction time (Zhao et al., 2018), and they are less efficient on various measures of visual search (Casagrande et al., 1997; De Gennaro et al., 2001; Dixit et al., 2012). Even spatial orienting is adversely

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impacted by sleep deprivation, as reported by Mander et al. (2008). Their participants completed a Posner cueing task after being fully rested or following 34-36 hours of wakefulness. Sleep-deprived participants not only made more errors than rested participants, but failed to show the usual benefits associated with predictive cues.

*Hydration*

Numerous studies suggest that hydration impacts both athletic performance and attention (Barr, 1999; Murray, 2007). Smith et al. (2012) asked euhydrated and dehydrated golfers to hit golf balls toward a target that was 110 m, 125 m, or 140 m away. Following this, participants were shown images of golf courses and were asked to estimate distances to flags set on these courses. Results showed that euhydrated golfers hit the golf ball further and more accurately than dehydrated golfers and they also made more accurate distance estimations. Magee et al. (2017) also reported that euhydrated golfers required fewer strokes to complete a round of golf than dehydrated golfers. More generally, studies show that dehydration impairs aerobic and endurance exercise performance (Cheuvront et al., 2003), and that hypohydration reduces performance on measures of strength, power, and high-intensity endurance (Judelson et al., 2007)

A set of studies by Edmonds et al. (2013) provide complimentary evidence that water consumption and hydration is beneficial for attention. In one study, Edmonds and Burford (2009) assigned children to a condition where they were offered and encouraged to drink water, or a control condition. Participants in the water group consumed on average 200ml of water, and approximately 20 minutes later all participants completed a visual search task called letter cancellation. This task allowed participants one minute to identify all instances of a target letter (e.g. the letter "U") on a 20 by 20 spatial grid containing distractor letters (e.g. "O", "V", and "C"). Participants in the water group identified more targets than participants in the control group, and subsequent studies have reported similar findings (e.g. Booth et al., 2012; Edmonds & Jeffes, 2009).

Edmonds et al. (2013) extended these findings to adults. Participants completed a letter cancellation task and were then assigned to an expectancy or non-expectancy condition. In the expectancy condition participants were informed about the beneficial effects of water on cognition, while in the non-expectancy condition no such information was given. Participants of both groups were then further assigned into a water consumption or no consumption condition, and all participants then completed an additional letter cancellation task. Participants who received water went on to show greater improvement compared to those who did not receive water, regardless of whether they had been assigned to the expectancy or non-expectancy condition.

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### *Environmental conditions*

#### *Thermal Stress*

Thermal stress is common in sports settings and has been found to reduce athletic performance (Maughan et al., 2010; Racinais et al., 2015). Research here includes findings that thermal stress increases dehydration, leads to physiological strain, reduces VO.max (González-Alonso & Calbet, 2003; Nybo et al., 2014), and is associated with longer time to complete a marathon as well as lower power output when cycling (Ely et al., 2007; Tucker et al., 2004). To mitigate the negative impact of thermal stress a variety of techniques, collectively referred to as pre-cooling, have been adopted by athletes. These techniques involve reducing core body temperature prior to participating in a sporting event. Pre-cooling techniques include consuming cold liquid, immersion in cold-water, application of cooling packs, and wearing cooling vests. A review by Wegmann and colleagues (2012) found that pre-cooling is effective, and especially so for activities that rely on endurance.

Thermal stress does not seem to impair performance on simple cognitive tasks, but appears deleterious for demanding and complex tasks (Hancock & Vasmatzidis, 2003; Taylor et al., 2016). For example, in studies by Sun et al. (2012) and Liu et al. (2013) participants completed the attention network test (i.e., several variants of spatial orienting and flanker tasks) under ambient thermal conditions of 20° C or 50° C. An alerting measure was derived by comparing response times on trials on which a target arrow was preceded by a central cue, with response times to the same target without a cue. A spatial orienting measure compared the difference between response times to target arrows appearing in the same location as the cue, to response times for targets in another location. Lastly a measure of attentional control was derived from trials on which the target arrow was flanked by distractor arrows that were congruent in their orientation versus trials on which they were incongruent (i.e., a flanker task). Thermal conditions had no effect on the alerting and spatial orienting measures, however thermal stress was found to impair performance on the more demanding trials reliant on attentional control.

#### *Competitiveness*

Sports are by nature competitive and it is often believed that competition improves athletic performance. For example, the presence of an athletic rival predicts faster race times on the running track (Kilduff, 2014) and cycling circuit (Corbett et al., 2012), and maximum bench-press performance increases in the presence of spectating competitors (Rhea et al., 2003). Rivalries among sport teams also influence which strategies are more likely to be adopted. Kilduff et al. (2010) had sportswriters rate the rivalries of various NCAA men's basketball teams and compared these ratings with several in-game statistics. They reported that defensive

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strategies tended to increase when strong rivals competed with one another (e.g. there were a greater number of blocked shots).

Competition conversely has the potential to disrupt the quiet-eye. Wilson et al. (2009a) tracked the eye movements of basketball players performing free throws after they were given instructions to either do their best or instructions that their performance would be compared to other players. Participants in the comparison group reported greater anxiety, made more fixations, had shorter quiet-eye durations, and overall had lower free throw accuracy. This same group of researchers (Wilson et al., 2009b) tracked the eye movements of soccer players while they completed a goal-scoring task following similar instructions. Comparable results were obtained as soccer players in the competitive group reported greater anxiety, made more fixations, had longer fixation durations, and tended to kick the soccer ball more centrally, and therein closer to the goalkeeper.

There are other studies reporting that the quiet-eye is unaffected by competition. In studies by Vine and Wilson (2010) and Vine et al. (2011) elite golfers and non-golfers completed a quiet-eye training condition or control condition. Golf putting performance was then assessed in a neutral or competitive context. In the neutral context, participants putted without guidance or training advice, whereas in the competitive context participants were told that their performance would be compared to others and that the participant with the best performance would receive a cash reward. The results showed no group differences when putting under neutral conditions. However, in the competitive context, participants who had prior received quiet-eye training maintained an optimal quiet-eye and displayed greater putting performance.

Observational research also suggests that competition can narrow attentional breadth. Rogers and Landers (2005; also see Rogers et al., 2003) had soccer players perform a peripheral visual target detection task using an ophthalmologic perimetry device. Participants fixated on a central marker while trying to detect dim spots of light that progressively advanced toward the center of the display. Detection rates were averaged across trials for each participant to provide a measure of attentional breadth. Participants completed this task, as well as reported their subjective levels of anxiety before practice and before a competitive game. Prior to competitive games, athletes were found to report greater anxiety and had narrower attentional breadth than when tested prior to practice games.

Research conducted in the laboratory also finds that competition impacts speed of flanker task response times. Iani et al. (2014) had pairs of participants complete a flanker task under cooperative or competitive conditions. Participants were told that either the best performing pair or the best performing individual would receive a cash reward. These instructions were aimed at promoting a cooperative versus competitive context, respectively. Participants in the competitive condition generally had faster response times than participants in the cooperative condition.

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### *Distraction*

There are numerous potential sources of visual distraction in many sports settings, including sudden and unpredictable movement from other players, camera flashes, banners, and gestures made by audience members. Sometimes distraction is used intentionally by an athlete to interfere with the performance of an opposing player. Wood and Wilson (2010) studied the effectiveness of one such technique, by having soccer players shoot penalty kicks against a goalkeeper who was either stationary or attempting to distract the kicker with hand gestures. The results showed that shots were not only kicked closer to the goalkeeper in the distraction condition, but that the goalkeeper also made more saves. An interesting interaction was also reported involving distraction and competition. In a high-competitive context the eyes of penalty kickers fixated more on the distracting goalkeeper than in a low-competitive context, suggesting that the penalty kicker is especially vulnerable to distraction as competition and anxiety increases. Other evidence suggests that the mere presence of a goalkeeper is enough to bias shot accuracy, as penalty kickers shots are more centrally located when a goaltender is present (Navarro et al., 2013). One strategy suggested to overcome this bias is for penalty takers to habitually practice routines that reduce the influence of goalkeeper distraction (Kurz et al., 2018).

Furley et al. (2017) asked whether similar results to those of Wood and Wilson (2010) could be found during actual football gameplay. They reviewed video footage of penalty shootouts from the FIFA World Cups (1986-2010) and the UEFA European Football Championships (1984-2012). Goalkeepers were classified as either attempting to distract the penalty kicker or not, and goalkeeper performance was rated on 5-point scale (e.g. 5 points were allocated for successfully blocking a shot, 4 for a near miss, etc.). The results showed that a greater number of saves were made when the penalty taker was judged to be focusing on the goalkeeper. Furthermore, goalkeepers attempting to distract the kicker were more successful on the 5-point scale used to assess goalkeeping performance.

Fulton et al. (2014) examined a different type of visual distraction as experienced when golf-putting. Specifically, they assessed whether the flash of a camera when putting disrupted the quiet-eye and lead to reduced golf performance. They tested this hypothesis with members of a university golf team, who performed a putting task in either a low-pressure condition, or a high-pressure condition meant to elicit competitiveness and anxiety. Regardless of condition on a subset of putting trials a camera flash was set to distract participants and disrupt quiet-eye maintenance. The result showed that putting accuracy was not reduced on camera flash trials, and participants did not differ in reported anxiety, despite the experimental manipulation. However, replicating much previous work, a longer quiet-eye period just before the put was correlated with putting accuracy. Moreover, quiet-eye duration tended to be longer on camera flash trials. A speculative account is that the camera

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flash contributed to both an increased quiet-eye duration and distraction, with the benefits of the increased quiet-eye compensating for the costs of the distraction.

The finding that distraction impairs visual search performance in the laboratory is one of the most robust findings in all of behavioral research. In particular, it is well established that the magnitude of distraction is directly related to the visual similarity between distractors and the target (Duncan & Humphreys, 1989; Liesefeld et al., 2016; Wolfe, 1998). Research by Chieffi et al. (2001) further suggests that biases introduced through visual distraction may impact kinematic motion. Participants in this study were required to draw a straight line between two spatially distant dots on a screen with a non-inking stylus. These two target dots could be connected by a distractor stimulus in the form of a straight line or a convex line. Participants were instructed to ignore these distractors and draw as straight a line as possible between the two target dots. The results showed that hand trajectories were biased by the connecting distractor lines, as hand trajectories curved left given a left-convex connector, and right given a right-convex connector. In a follow-up study, visibility was reduced such that participants could not see their hand when completing the task, and therein had limited visual feedback concerning their hand movement. Now all hand trajectories were leftward biased across study conditions, with this bias also being greatest in the left-convex distractor condition.

### *Individual differences*

#### *Personality*

Personality refers to the relatively stable characteristics of an individual with regard to their cognitive appraisals, emotional responses, and behavioral choices. Many frameworks of personality have been proposed, with the most popular being the big five theory (McCrae & Costa, 1987). In this theory, personality is categorized by the relative weightings of one's score on five dimensions: neuroticism, extraversion, openness, agreeableness and conscientious. High neuroticism scores reflect relatively higher levels of emotional instability, irritability and anxiety. High extraversion is associated with being more social, talkative and outgoing. High openness denotes relatively higher levels of curiosity, creativity and the desire for new experiences. High agreeableness is linked to relatively higher levels of social compassion and cooperation. Lastly, individuals scoring high in conscientiousness tend to be those who are punctual, dependable, and organized.

Athletes who compete at elite levels (i.e. international and national levels of competition) tend to be less neurotic, more conscientious, and more agreeable than athletes who compete at lower levels (i.e. university and club levels; Allen et al., 2011). Soccer players who score higher in conscientiousness than other players also tend to be those who are more successful, i.e., they play more games in a season, attempt more shots, and

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are rated higher on coach-ability and in game performance. On the other hand, soccer players who score higher in neuroticism than other players tend to be less successful in their athletic pursuits when assessed by these same standards (Piedmont et al., 1999). Studies comparing athletes from different sports also reveal that individual-sport athletes tend to score lower on extraversion than do team-sport athletes (Allen et al., 2011; Eagleton et al., 2007).

Neuroticism has been suggested to impair attentional control in several laboratory studies. Wallace and Newman (1998) had participants perform a task in which two letters (e.g. "V" and "Z") were predesignated as targets. Each trial consisted of five search displays, with each display depicting three letters and each shown in quick succession (250 ms each). After viewing all five displays participants indicated whether in any display a target letter had appeared, and the critical manipulation was that some displays contained a novel distractor shape (e.g. a dollar sign). The results showed that women scoring higher on neuroticism, relative to those scoring lower, tended to miss targets more often on trials where novel distractors were present. These results suggested that novel distractors were less successfully filtered and inhibited thereby degrading task performance.

Some research suggests that neuroticism may elicit inhibitory control even when it is not warranted. For example, in a study by Sosic-Vasic et al. (2012) participants were asked to identify a central stimulus among others (i.e., a flanker task) as being either an "R" or a "U". When the letters "P" or "V" were presented in the center instead, participants were instructed not to respond at all. Among their results, individuals with higher scores on neuroticism were more likely to withhold a response on target trials, thereby incorrectly exerting inhibitory control when it was not appropriate to do so. While neuroticism has been implicated in inhibitory control, it is also worth noting that some studies report null or mixed results, making a more definitive interpretation between neuroticism and inhibition difficult to attain (Avila & Parcet, 2001; Fleming et al., 2016). The extent to which neuroticism impacts inhibitory control may be dependent on other related factors, like impulsivity, which itself correlates with neuroticism (Hair & Hampson, 2006; Mao et al., 2018).

The ability to shift attention within a visual environment has been found to covary with personality in numerous studies. Newton et al. (1992) reported that individuals who scored higher in extraversion were faster to correctly report a target as present within a search display, as well as absent, relative to individuals who scored lower. They also found that individuals who scored higher in neuroticism were slower to identify a target as absent. More recently Biggs et al. (2017) measured the personality traits and visual search performance of U. S. Transportation Security Administration (TSA) officers and found that officers lower in conscientiousness were more likely to miss a target during the search task. Peltier and Becker (2017) also examined whether personality differentiated performance on a search task involving relatively rare

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targets (e.g. 10% of trials) and found that introverts seemingly had greater task accuracy, although this may have been at the cost of longer response times.

*Age*

The question of whether there is an optimal age for athletic performance has been examined in various studies. Schulz and Curnow (1988) reported that Olympic runners as well as professional tennis players displayed peak performance approximately in their early to mid-twenties. Peak performance for Olympic swimmers was even younger (approximately 20 years), whereas for professional baseball players and golfers it was older (28 and 31 years, respectively), although for golf there also appears to be a more recent trend toward younger ages.

At the other end of life, advancing age tends to denote athletic decline. Bortz and Bortz (1996) examined athletic performance of U. S. Masters runners, rowers and swimmers and found an average performance decline of 0.5% per year from the ages 35 to 70, with a more rapid decline after age 65. A similar finding was reported with national champion swimmers (Rubin et al., 2013; Rubin & Rahe, 2010) showing that after approximately age 35 performance declines by about 0.6% each year, with more marked deterioration following 70. These results further align with more specific findings showing that older age implicates losses in muscular fitness as well as functional fitness (Bross et al., 1999; Milanović et al., 2013).

Attentional processes measured in the lab are also sensitive to age and show developmental periods of growth, maturation, and decline. Trick and Enns (1998) and Hommel et al. (2004) studied visual search among participants aged 6 through 89 and reported that young adults performed faster than either children or older adults. Further analysis revealed that children were especially sensitive to distractors, suggesting an inability to filter superfluous and irrelevant information. Older adults alternatively showed markedly slower performance on target-absent trials, suggesting older adults may be adopting a more cautious or accuracy-favoring approach when searching. In Bedard et al. (2002) participants aged 6 through 82 completed a stop-signal task. Their results showed a similar inverted U-pattern, such that stop-signal reaction times improved with increasing age throughout childhood and showed marked decline into older adulthood.

More generally, older age implicates cognitive loses (Salthouse, 2009; Schaie et al., 2004), including age-associated decrements on trail making tasks (Hamdan & Hamdan, 2009; Kennedy, 1981; Titova et al., 2016; Tombaugh, 2004), useful field of view tests (Ball et al., 1988; Sekuler et al., 2000), letter cancellation tasks (Uttl & Pilkenton-Taylor, 2001; Warren et al., 2008), and numerous visual search tasks (Brennan et al., 2017; Hommel et al., 2004; McPhee et al., 2004; Trick & Enns, 1998). This decline is often hypothesized to be the result of general neuronal slowing and/or less efficient inhibitory control that accompanies old age

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(Brennan et al., 2017; West & Alain, 2000), although it may also reflect a change in technique or strategy (e.g. being more cautious; Hommel et al., 2004).

Even among studies reporting that older adults can improve attentional processes with specific training, their performance still typically remains at a level well below younger adults. For example, Folk and Hoyer (1992) had younger and older adults complete a Posner cueing task in which the target appeared in one of four boxes and was preceded by a flash cue near one of these boxes. The cue could be valid (i.e. appearing near the target box), absent, or invalid (i.e., appearing near a non-target box). When 200 or 250 milliseconds separated the cue from the target, older adults performed better on valid-cue trials compared to no-cue trials. Younger adults did not show this benefit but were also on average 160 milliseconds faster than older adults. In a second experiment, the cue was a centrally presented arrow that pointed predictively toward one of the four boxes. Younger adults again showed no difference between valid-cue and no-cue trials, whereas the performance of older adults was reduced on any trial with a cue, whether it was valid or not. Seeking to improve performance in older adults via task feedback has also at times been found to have deleterious effects. Drueke et al. (2012) compared the influence of end-of-block feedback versus no feedback on a flanker task in both younger and older adult participants. In younger adults, feedback resulted in faster response times and an increase in errors, implying a shift toward a more liberal response criterion. In older adults, feedback led to more errors without any change in response time.

### *Gender*

Athletic records are often segregated by sex. Putative reasons for this division include differences in muscular and physiological structure between men and women. But it has been difficult, if not impossible, to separate the potential underlying biological differences between the sexes from many cultural, ideological, and political viewpoints that have entrenched this division. One of the reasons making it difficult to disentangle biology from culture is that widely-held cultural views contribute to reduced interest and involvement in sports by girls and women. There is much research documenting that girls and women are less involved and less likely to engage in sports than are boys and men (Deaner et al., 2012; Eime et al., 2016; Hallal et al., 2012). This is beginning to change, but not enough yet to allow clear separation between these two classes of factors.

Silverman (2006) noted that sex differences in Olympic records have narrowed over passing decades. Taking the 100 m dash as an example, when women first competed in this Olympic event in 1928, the winning race time for women was 12.2 s whereas the winning time for men was 10.8 s, a difference of 1.4 s. When considering more recent years (2004, 2008, 2012 and 2016), the winning race times for men were 9.85 s, 9.69 s, 9.63 s, and 9.81 s, and for women were 10.93, 10.78, 10.75 and

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10.71 (Olympic Games, 2020a; 2020b). Thus, in the two most recent decades the difference between men and women on the 100 m dash has remained approximately constant at a 1 second difference favoring men. It is still too early to say whether this difference reflects the hard limits of biology or whether it still simply reflects the differential involvement in and commitment to women's versus men's athletics.

The increased participation of women in elite athletics over the past 100 years can be seen in almost every sport. For instance, within the Winter Olympic games, participation has been steadily rising over the past several decades (Olympic Games, 2020c). Participation by women increased from 15.7% of athletes in 1952 (Oslo), to 21.5% in 1984 (Sarajevo), and more recently to 41% in 2018 (PyeongChang). Some evidence suggests that men and women may be drawn to different sport types (Eime et al., 2016), but this too is difficult to disentangle from cultural norms and sport availability.

In the laboratory, men are often measured with faster reaction times than women (Ballard, 1996; Bleecker et al., 1987; Dykiert et al., 2012). This finding was replicated in Lum et al. (2002), where nonathletic men had generally faster reaction times on a Posner cueing task than did nonathletic women. However, this difference vanished when comparing athletic men with athletic women at the university level. This suggests that when women are regular practitioners of a sport their reaction times in the lab are comparable to men and generally faster than nonathletic women. Alves et al. (2013) tested athletes (volleyball players) and nonathletes on a battery of cognitive tasks. Some of the results showed athletes and nonathletes to be comparable (e.g. accuracy on a useful field of view task), whereas in other tasks athletes outperformed nonathletes (e.g. faster stop-signal reaction time). On a flanker task, male nonathletes were faster than female nonathletes, and female athletes were faster than female nonathletes. Yet, there were no reaction time differences between male and female athletes, consistent with Lum et al. (2002). Silverman (2006) has reported that even in the general population, reaction time difference between men and women has decreased steadily in recent decades, coinciding with increased participation in sports amongst women.

Many laboratory studies of attention do not break down their data by gender, making estimates of gender differences difficult to determine. One exception are studies of trail making, where many studies do not find gender differences (Arnett & Labovitz, 1995; Bezdicek et al., 2012; Kennedy, 1981; Lu & Bigler, 2002; Soukup et al., 1998; Tombaugh, 2004), though some do (Beeri et al., 2006; Hamdan & Hamdan, 2009). More narrowly, some studies report that men are faster to complete trail making A, but are similar to women on the more demanding trail making B (Giovagnoli et al., 1996; Seo et al., 2006). In some studies where men outperform women, this difference is decreased when age and education are also taken into account (Campanholo et al., 2014).

It seems fair to summarize this section on gender differences on attention with two statements. First, there are many documented reports

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of a male advantage for both athletic endeavors on the field and on laboratory tasks of attention. Second, we are still a long way from being able to attribute these reported differences to either immutable biological differences between the sexes or cultural practices. Gender differences that are observed on the field and in the laboratory are subject to modulation by many contextual variables, including genetics, hormones, culture, behavioral practices, motivation, and training.

## The evolving nature of attentional theory

Now that we have discussed the relations between sports and laboratory measures of attention (section 2), and we have reviewed the empirical relations that exist between three classes of sport-relevant factors (behavior, environment, individual; section 3), we are ready to consider how theoretical accounts of attention are able to accommodate these findings. But first a word of caution. There is currently no widely accepted way of understanding selective attention, even for experts in this domain (e.g. see Gaspelin & Luck, 2018; Hommel et al., 2019; Theeuwes, 2018; Wolfe, 2018). Theoretical ideas have been in constant flux for the past five decades and the theories themselves have tended to focus on particular methodological paradigms. Therefore, in this section, we will seek to understand the empirical databases we have reviewed in light of the evolving theoretical frameworks that cognitive scientists have used to understand attentional processes. Indeed, it is our view that a careful consideration of the data in the previous sections can help to contribute to a fuller understanding of attention. To phrase it as a proposal, we are suggesting that a consideration of sports and athletics can refine and further develop theories of attention.

Figure 1 illustrates four important steps in the evolution of frameworks of attention over the past half-century. These are admittedly simple caricatures of the much more nuanced ideas expressed by the proponents of each of these views. However, we offer these sketches as a way to organize and facilitate the present review, and to visually describe how the data we have discussed can be accommodated (and sometimes not be accommodated) by the theoretical ideas in each of these four frameworks.

We begin our review of theoretical frameworks with the saliency map (Figure 1A) for two reasons. First, our review is focused on visual selective attention and because vision is organized neuroanatomically in a topographic way, a map metaphor is a natural starting point (e.g., Koch & Ullman, 1985). Second, subsequent frameworks of attention, while criticizing aspects of the original saliency map, nevertheless held on to the fundamental idea that priority for processing was resolved in a spatial way. By Bisley and Goldberg's (2010, p.3) account, saliency maps were the origin from which priority maps later emerged: "Our hypothesis is that neurons in [lateral intraparietal area] act as a priority map. This hypothesis is strongly based on the concept of the saliency maps of Koch, Itti, and colleagues." When Awh et al. (2012, pp. 437-438) went on to develop the integrated priority map, they wrote: "To provide a more comprehensive

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taxonomy, we propose a theoretical framework that extends the well-known construct of a priority map that integrates multiple selection influences." They were followed by Todd and Manaligod (2018, p. 122), who wrote "The [Priority State Space] framework is informed by the dynamic nature of priority maps as they have been conceptualized (Bisley & Goldberg, 2010)... Building on previous models [e.g., (Awh et al., 2012).], we propose three broad categories of attentional guidance." In the last framework we consider, the dynamic model of attention proposed by Ristic and Enns (2015b), many of the assumptions of these earlier frameworks are reassessed, but the notion of a spatial map that expresses the outcome of visual selection is not disputed.

### *The saliency map*

In the beginning – or at least in the beginning of attention as a serious theoretical concept within the cognitive sciences – visual attention was understood using a variety of metaphors (Di Lollo, 2018), including a *filter* (Broadbent, 1958), a *spotlight* (Posner et al., 1980), a *zoom lens* (Eriksen & St. James, 1986), a *limited resource* (Lavie & Tsal, 1994), and *glue* (Treisman & Gelade, 1980). Moreover, these metaphors tended to characterize the visual world as interacting with attention through one of two ways: bottom-up salience and top-down control. Bottom-up salience refers to the built-in or hard-wired features of the visual brain, fine-tuned by evolution or through extensive practice, to orient attention towards local regions of the visual field that are distinct in color, geometry, texture, motion and other basic featural properties. Neurologically, these featural properties would be detected via the first-forward sweep of neural activity following the onset of a visual scene, and attention accordingly distributed to these distinct portions of the visual world. In the typical course of everyday viewing, new scenes are presented to the visual brain on the order of 3 or 4 per second. This is because the eye typically makes saccades (short ballistic movements from one location to another) at this rate, placing new information on to retinal cells with every new fixation. One of the primary predictors of where the eyes will land next was then thought to be the relative strength of neural activation corresponding to the distinct featural properties that are detected in a given fixation. This was the initial conceptualization of *salience* (Duncan & Humphreys, 1989; Wolfe & Horowitz, 2004; 2017).

Bottom-up salience provided a mechanism through which attention could be orientated to unique locations in the world that might be worthy of closer examination. Posner (1980) likened these attentional shifts to physiological reflexes. Treisman and Gelade (1980, p. 107) further proposed that a "master map of locations" must exist somewhere in the visual brain, and that this map contains all the spatial locations that had been detected via their featural salience. This idea was further refined by Koch and Ullman (1985), who proposed that a *saliency map* combines all the neural activity elicited by independent visual feature detectors into a

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common density distribution, which then determined the allocation of attention on a winner-take-all basis.

Consider an example based on luminance differences. Every visual scene can be thought of as being represented by a luminance map, the topography of which registers the locations where luminance differences are greatest. Other simple visual features, including edge-orientation and motion, are represented by their own saliency maps. These individual feature maps are combined to produce a global saliency map, the topography of which indicates where attention is directed next based on the most highly conspicuous (i.e., salient) regions of a scene.

But spatial orienting is not governed entirely by bottom-up inputs. Individuals can voluntarily orient and guide attention based on their goals, expectations, and desires. This is referred to as top-down control. Although there is much consensus about what constitutes top-down control, it is worth noting that debate exists here as well (e.g. Egeth, 2018; Gaspelin & Luck, 2018). For theorists like Posner (1980), top-down control allowed attentional orienting to be governed by the information given in an arrow or other symbolic cue. Other theorists such as Treisman and Gelade (1980) saw top-down control as the mechanism that permitted target identification based on two or more simple features (called feature conjunctions). Others still, like Eriksen and Eriksen (1974), saw top-down control as a regulatory process that allowed one to inhibit undesired responses. Top-down control has also often been characterized as an effortful process (Bruya & Tang, 2018; Kahneman, 1973).

Neurologically, top-down control relies on both feedforward and re-entrant neural processing. An initial forward sweep of neural activity is elicited by the featural properties of a scene, but it is not until re-entrant processing occurs that those features can be selectively attended to (Lamme & Roelfsema, 2000). Because this form of control requires one or more cycles of neural activity (feedforward and feedback sweeps of neural activity), it also takes longer to accomplish than bottom-up control (Baluch & Itti, 2011; Katsuki & Constantinidis, 2014). Consequently top-down control is often referred to as the slower or more timely process in contrast to bottom-up processing.

Bottom-up and top-down processes must, of course, be coordinated during the course of everyday activities. Bottom-up processes can be viewed as a form of novelty bias, whereas top-down processes can be viewed as a form of familiarity bias. Both biases are equally important, and must be held in tension with one another, for the survival and success of an organism. Theorists trying to describe the interplay between these two forms of control, sometimes refer to the existence of a *priority map* (often preserving the term saliency map for strict bottom-up processes; Bisley & Goldberg, 2010; Bisley et al., 2011). The priority map can be understood as a description of the current state of the spatial orienting system, a state that is the integrated sum of the spatial locations that have been activated by bottom-up processes, along with the spatial locations that have been identified by top-down processes.

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Neurophysiological researchers have proposed that the candidate brain region that might be home to such a neural structure is the lateral intraparietal area (LIP). LIP is sensitive to simple visual features such as luminance (Balan & Gottlieb, 2006; Bisley et al., 2011), receives input from the anterior cingulate cortex (ACC) and insular cortex (IC) which are implicated in top-down processing (Bisley et al., 2011), and communicates with areas like the frontal-eye fields (FEF) which are involved in both bottom-up and top-down controlled spatial orienting (Bisley et al., 2011; De Haan et al., 2008). Other brain regions have been proposed as well, including a more recent article by Bisley and Mirpour (2019) that suggests the LIP, FEF and superior colliculus reflect a *global priority map*.

It is important to note that the saliency and priority map frameworks were developed to account for both behavioral and physiological measures of attention in the lab. [1] These frameworks emphasized the commonality of attention mechanisms across individuals. For instance, consider the Posner cueing task, where the orienting of attention in response to a symbolic cue like an arrow may take ½ second longer or more to complete than orienting attention to the same location reflexively, as when a brief flash occurs in the visual field. This difference in time can be accounted for by the neural activity believed to be required for each type of orienting. Whereas reflexive orienting can be accomplished through an initial forward sweep of neural activity, voluntary orienting in response to a symbol requires re-entrant neural processing as well and therefore is a slower process.

A collateral consequence of this focus on brain-general processes common across people and settings was that it often ignored individual differences and situational dependencies. As such, it had no way to account for the sports-specific findings we reviewed in section one. For example, the finding that dynamic and static sports athletes, or even athletes within the same sport, show differential task performance is difficult to transparently represent within the saliency or priority map framework. The saliency map framework has even less to offer when modelling how behavioral practices, environmental conditions, and individual differences, each differentially impact attention as outlined in section 2. These and other limitations ultimately prompted researchers to look for new frameworks and theories through which to model attention.

### *The integrated priority map*

The brains of all organisms are constantly adapting to their surroundings based on experience and history. Adaptation can take on many forms, from peripheral changes in sensory receptor sensitivity, to subtle adjustments in cognitive representations based on recent events, to enduring changes in long term memory. This propensity toward adaptation at all levels means that when the human visual brain encounters an event it recognizes from the past it responds differently than if that event had never been experienced. Awh et al. (2012) addressed

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the importance of this sensitivity to history in their theoretical account of attentional selection. After examining a large body of research, they made the provocative theoretical proposal that stimuli that had recently been acted upon by an individual, and stimuli that had recently been associated with reward, were both given preferential treatment by the attentional system.

Awh et al. (2012) argued that when a particular stimulus draws attention because of its recent history of selection and/or reward, this cannot be classified as either bottom-up or top-down processing. Bottom-up processing does not fit because neither previous actions toward a stimulus nor its past reward potential alter its physical features. Top-down control does not fit because participants in many cases are not voluntarily deciding to treat these stimuli preferentially. Indeed, often it is explicitly in the interests of participants to ignore any past actions or reward of past-selection and reward appear to occur much more rapidly than traditional accounts of top-down processing would suggest. Awh et al.'s (2012) solution to this paradox was to propose the *integrated priority map*.

An important background study for the integrated priority map was completed by Maljkovic and Nakayama (1994). Here participants completed a visual search task where the target on each trial was a uniquely colored diamond (e.g. a single green diamond among red diamonds). The task was to indicate whether the left or the right tip of the target diamond was missing. The main finding was that when the target color was repeated on successive trials, the task was completed more rapidly. These results suggested that a recently selected feature is processed more efficiently and treated preferentially when it is encountered again.

Some evidence suggests that this priming of pop-out effect can occur for both task relevant and task-irrelevant featural properties. For example, Huang et al. (2004) had subjects view line segments, each of which were orientated 45° or 135°. Participants were required to report the orientation of the target line which was a line segment that was shorter or longer than all others (i.e., length and orientation were task relevant). Extraneous to this task, each line segment was also either black or white (i.e., color was task irrelevant). Among the results, when both target length and orientation were repeated across trials (task relevant features), response times were faster. Similarly when target length and color were repeated (task irrelevant), response times again were faster. Studies documenting these priming pop-out effects now number in the many hundreds, and include research showing the automaticity and perseverance of this effect over multiple trials (Kristjánsson & Ásgeirsson, 2019).

Another core set of studies leading to the integrated priority map pertain to reward. Research by Hickey et al. (2010a) exemplifies the burst of research over the past decade documenting how reward history impacts attentional selection. Here participants searched for a unique target shape (e.g. a diamond) among homogenous distractor shapes (e.g. circles). The task was to indicate whether the target shape contained a horizontal

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or vertical line. Following each correct response, participants received a reward either high or low in value. The critical manipulation, which was unrelated to task success, is that on some trials all shapes were the same color (e.g. red) whereas on other trials one of the distractors had a unique color (e.g. green). The main finding was attention became dependent on reward association. For example, if identifying a red target prompted high reward for a participant, then they were faster on succeeding trials when the target was again red. Conversely, if the target was red and highly rewarding on the prior trial, then performance was especially impaired if a distractor item was red on the upcoming trial. A task irrelevant feature in color had now seemingly gained importance through an association to reward.

More recently Munneke et al. (2015) examined the impact of reward on attentional orienting in the Posner cueing task. Here participants saw a predictive arrow aim toward one of two boxes, each of which could contain either a target letter ("P" or "S") or a distractor letter ("E" or "H"). One of the boxes also changed color at the same time as the letters appeared. This color change was random and so did not predict target location. But it did predict the magnitude of the reward that occurred post response (e.g. red meant no reward, yellow meant low reward, and green meant high reward). The responses of participants benefited not only from the predictive arrow, but highly rewarding colors led to faster response times when they cued the target letters and slower responses when they cued the distractor letters. Studies like these examining reward and attention now number in the hundreds (Anderson, 2016), including a study by Anderson and Yantis (2013) showing that rewarding stimuli continue to capture attention over half a year after an initial learning phase.

Awh et al. (2012) incorporated the results of selection history and reward history studies into a framework that has come to be known as the integrated priority map, as illustrated in Figure 1B. Stimulus history is given unique standing in this framework as a set of selection mechanisms that are distinct from traditional bottom-up mechanisms (relabeled as physical salience) and top-down mechanisms (relabeled as current goals). Humans preferentially attend to objects that were previously attended to in the past and to objects that are associated with reward, even if these objects lack salience and are unrelated to current task goals. These three factors (stimulus history, physical salience, and current goals) then operate in concert with one another, as weighted influences, to guide where attention is next most likely to be directed.

The addition of stimulus history to the priority map goes a long way toward explaining potential mechanisms that underlie attentional processes in athletes. For instance, the attentional flexibility characteristic of dynamic sport athletes may in part be driven through years of selection-priming experience. Hockey players during a competitive game might need to shift their attention from the hockey puck, toward teammates and opposing players, before resuming attention back onto the puck. In this

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example, it seems tenable that the perceptual properties of the puck (e.g. color, shape, size) may serve as primes for faster object re-identification.

Although the integrated priority map does not speak to how behavioral practices and environmental conditions influence attention, it does emphasize personal history. In doing so, it formally acknowledges that selective attention changes over time within an individual, dependent on that individual's history of prior selections and episodes of reward. Personal history, however, is more than individuals selecting stimuli and experiencing reward. Individuals gather experiences over time, form associations, and accumulate knowledge about the external world. To expand on these points, we next consider a framework known as the *priority state space*, which emphasizes longer time-scales of experience, along with semantic, statistical, and affective learning.

### *The priority state space*

Individuals learn continuously throughout life. This learning takes place over multiple timespans, from brief episodes of seconds and minutes, to intermediate periods of hours and days, to even longer timespans involving months and years. Much of the time this learning occurs effortlessly and without instruction, allowing for both subtle and profound differences to emerge between individuals as they develop idiosyncratic semantic, affective and statistical associations with objects and environments. Todd and Manaligod's (2018) priority state space framework is an effort to accommodate these forms of learning in the control of attention.

When individuals read a list of words such as "bed", "rest", "dream" and "wake", they may later recall reading the word "sleep", even though it was never encountered (Deese, 1959; Roediger & McDermott, 1995). Such false memories occur because these words share an underlying conceptual relatedness to one another. Objects we encounter everyday are also richly linked in our long-term memories to other objects via common uses, situational contexts, and emotional evocations. An example of how attention can be influenced by such knowledge comes from Moores et al. (2003), who asked participants to report the presence or absence of a naturalistic object amid distractors in a scene. On some trials the target (e.g. hammer) appeared with conceptually related distractors (e.g. nails) whereas on other trials the distractors were unrelated (e.g. flowers). On trials with conceptually related distractors, participants were slower and less accurate in reporting target absence.

Sometimes the association an individual has with a stimulus is strongly emotional. Öhman et al. (2001) reported that fear-relevant stimuli (snakes or spiders) were identified more quickly in a search task than were fear-irrelevant stimuli (flowers or mushrooms). Pflugshaupt et al. (2005) also reported that when spider-phobic individuals performed a search task they fixated sooner and closer to spiders during the initial viewing of a scene and then subsequently fixated further away from these stimuli than did non-spider phobic individuals. Spider-phobic individuals also

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tend to rate spiders as being larger in size, and faster in approaching speed, than non-spider phobic individuals (Basanovic et al., 2019; Shiban et al., 2016). In another stimulus domain, Bannerman et al. (2009) studied visual discrimination for faces and bodily configurations associated with different emotional expressions. They reported that targets merely suggestive of fear drew attention earlier and more quickly than neutral faces and body configurations. Collectively these studies imply that the emotional meaning of a stimulus itself can direct attention.

Environments are defined by statistical regularities in their spatial layouts and in the identity and locations of the objects they contain, thereby offering predictive information to guide attention. For example, the daily spatial regularities and temporal patterns of a university campus help a driver know where they are likely to find a parking spot. Similar regularities help a teacher predict when a classroom will be filled, and can assist an athlete in passing a ball to a location where a teammate (but not an opponent) will soon be present. The ability to learn spatial patterns and temporal regularities of an environment was originally studied using a laboratory visual search task called contextual cueing (Chun & Jiang, 1998). In this task participants identify targets amid distractors in the usual way, but unbeknownst to them the spatial distribution of the target and distractor items may either repeat or be entirely random on future trials. Although individuals do not typically recognize that a previous display configuration has been repeated, search performance is faster on such repeated displays.

Statistical learning of this kind has been studied in the athletic domain. In the Williams et al. (2006) study mentioned earlier, recall that semi-professional and recreational soccer players were tested for their new-old recognition of soccer sequences depicted as moving dots, and semi-professional players were both faster and more accurate than recreational players. This difference is consistent with the hypothesis that highly skilled athletes have a richer representation of the statistical regularities of a soccer game than do novices. More broadly applicable to this idea, Brockmole et al. (2008) had participants search for a target letter ("T" or "L") embedded in a chessboard display that was consistent with the rules of chess. When these displays were repeated on a later trial, the benefit of repetition was found to be greater for chess experts than for novices. In a second study search displays were randomly generated, thereby removing the regularities of chess, and here the search benefits of repetition were greatly reduced in the chess experts.

Todd and Manaligod's (2018) priority state space is a natural evolution of the integrated priority map (Awh et al., 2012). In addition to recognizing the importance of a participant's history with a stimulus, it also incorporates semantic, affective, and statistical learning effects into the control of attention. We have noted this in Figure 1C by adding three inputs to the history dimension at the top of the diagram (i.e., semantic, affective, statistical). But there are other differences that distinguish this framework from previous ones as well. Whereas emotion is considered a bottom-up input within the integrated priority map

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(Figure 1B), it has been moved to the history factor within the priority state space (Figure 1C). Consequently, these two frameworks differ in how they see emotional content interacting with selective attention. In the integrated priority map (Figure 1B) the featural properties characteristic of a spider, including its shape, size, motion, and color, are what draw and guided attention. This in turn provides rationale for why benign objects sharing similar featural properties with a spider can mistakenly on first glance automatically and involuntary attract attention. In contrast, the priority state space (Figure 1C) views the interaction between emotion and attention as arising through affective learning processes refined over the course of an individual's life. There are many potential implications from this distinction. For instance, the integrated priority map suggests that fear is elicited through the involuntarily and automatic processes characteristic of bottom-up inputs, whereas the priority state space models fear as occurring through learned associations which comparatively posits greater capacity for change and modification through additional experience, learning, as well as therapeutic treatment.

Another advance offered by Todd and Manaligod's (2018) priority state space (Figure 1C) is a change in metaphor. In the earlier frameworks, attention was likened to a *map*. Now it is referred to as a changing landscape. Todd and Manaligod (2018, p. 133) write that the "[Priority state space] is a conceptual landscape of context-specific priority map possibilities". In doing so, they opt for a metaphor that emphasizes attention as being flexible and changing over time. To reflect the ever-changing nature of the attentional landscape, as it is influenced by history and context over different time scales, Figure 1C uses a dotted circle to enclose the priority state space, rather than the solid circle as in previous frameworks.

How does the priority state space accommodate the data summarized in the third section of this review, where we discussed how athletics and attention were influenced by a variety of behavioral, environmental and individual factors? Clearly, it goes a long way toward making room for the experiences, associations, and knowledge individuals have accumulated over their lifetimes. Athletes who have dedicated large portions of their lives to a specific sport are likely to learn statistical regularities associated with their sport. Yet, not all the data considered in that section are accounted for. For example, physical properties of the environment, such as thermal stress (with its' attendant consequences on physiology) do not seem to have a role to play within this framework. The same can be said for individual practices such as adherence to exercise, maintenance of hydration, and sleep. There is seemingly no direct way to account for these factors within the priority state space framework. Finally, the influence of individual differences in personality and age are given little defined role within this framework. To accommodate these remaining factors, we turn to a final framework that challenges a number of conventional assumptions about attention.

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*Dynamic attention*

The historical position taken in the cognitive sciences is that attention — whatever it is — acts as a gatekeeper of perception, cognition, and action. This can be seen in the popular metaphors used to refer to the saliency map (e.g., spotlights, filter, resources, glue). These metaphors imply that attention is an active agent. Attention is something (e.g., a gatekeeper of some kind) and it does things (e.g., it limits other regions of the brain from being influenced by all the potential stimuli reaching our sensory organs and ultimately conscious experience). Similar parallels are also implicated in the frameworks referred to as the integrated priority map (Figure 1B) and the priority state space (Figure 1C). These frameworks all hold to the position that there are central mechanisms of selection, somewhere in the brain, that are relatively stable over time, but that can be influenced by factors such asbottom-up salience, top-down goals, and the learning history of the individual over various time scales. But there is now a growing realization among attention researchers, spurred in large part by the kinds of data we have reviewed in the previous sections, that it may be time to give up the search for an attention mechanism that acts as the gatekeeper for the rest of the brain.

Instead, some theorists are seriously considering the possibility that what we call attention is the outcome of a vastlyinterconnected brain in which local decisions are constantly being integrated in real time (Anderson, 2011; Cisek & Kalaska, 2010;Hommel et al., 2019; Kim & Kastner, 2019; Krauzlis et al., 2014; Ristic & Enns, 2015a). To be fair, we must point out that this position was proposed more than 100 years ago (Sudduth, 1895), though it is equally clear that it was not taken seriously within the cognitive sciences until recently. Taking the *attention-as-outcome* perspective suggests that when we measure attention in the laboratory, or on the field, what we call attention is the integrated outcome of a vast network of local decisions. Attention in this framework has become the net effect of many local decisions; it is no longer a reified cause of selection. Attention in this view — when measured as a dependent variable — is still something, but it is something that depends on a host of interconnected factors, including all the factors we have catalogued in the previous sections of this review. Attention is not a uniform or static structure that can be identified in a brain scanning experiment, but rather is the behavioral outcome of numerous local brain processes being integrated with one another. In the diagram illustrating this framework (Figure 1D) we have chosen to remove the central circle labeled *attention* that featured prominently in the other frameworks, in order to better reflect this change in status from attention as an independent factor (a cause) to attention as a dependent variable (an effect).

This fully *dynamic* conceptualization of attention (Ristic & Enns, 2015b) naturally accommodates the empirical findings that selective attention, and action, are influenced by environmental factors, behavioral practices, individual differences, and also by the built-in selective mechanisms inherited through evolution by each of the sensory systems (e.g., orienting reflexes in vision, audition, and touch; disgust responses to bitter tastes; and many more). Taken together, these factors all help determine why, at any given moment, some information is selected for privileged processing, in order to facilitate appropriate actions or conscious experience, and at the same time why other information is ignored or inhibited. The important role played by so-called top-down processing (Figure 1A), current goals (Figure 1B), and executive functions (Figure 1C) have been subdivided further into the behavior, environment, and individual classes of factors shown in Figure 1D. For example, if someone places more effort into a visual search than another participant, perhaps by adopting an active strategy to willfully inspect potential target items in a systematic way, then they will be less able to simultaneously perform a second task (i.e., to multi-task; Smilek et al., 2006), and their eye movement patterns will be measurably different from those of participants who engage in a more passive strategy (Watson et al., 2010). Moreover, in some situations an active strategy leads more directly to successful searches (Brennan et al., 2011), whereas in other situations a passive strategy is most beneficial (Watson et al., 2010). Furthermore, some participants are more likely to engage in an active strategy spontaneously, while other participants tend to adopt a passive strategy (Brennan et al., 2011). Thus, instead of referring to all these effects as undifferentiated top-down control, the dynamic framework opts for a description that permits top-down control to arise through the combined effects of the behavioral actions one is completing, the ongoing assessment of environmental demands, and the cognitive approach favored by an individual's personality.

This framework for attention also fundamentally alters the questions that are most important for the field to explore and to understand at a theoretical level. For example, instead of searching for the brain region that may be responsible for selective processing in some task, the search for neurophysiological substrates turns instead to how brain regions may be communicating with one another in order to produce the coordinated activity we refer to as an act of selective processing. The labelling of a single brain region as responsible for selective attention is misguided in this view, as it continues a tradition of looking for distinct brain regions that may be specialized to perform a unique act of selection. Using the frontal eye fields as an example, neurons here are implicated in sensory processing, visual target discrimination, and preparation of eye-movements (Kirchner et al., 2009; Krauzlis, 2008; Peng et al., 2008). Hence a single brain region may be involved in many aspects of sensation, cognition, and action rather than being specialized for solely one of these functions (Cisek & Kalaska, 2010). Such heterogeneity of function in a single region of the brain suggests that to understand how selective processing is accomplished by a given region, it is better to consider how, and to which other brain regions, it communicates.

Today's theorists point to several different brain networks involved in attention control. One critical network includes multiple brain areas

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in the frontal and parietal regions of the cortex, located along the intraparietal sulcus, the superior parietal lobule, and the frontal and supplementary eye fields (Kim & Kastner, 2019; Silver & Kastner, 2009). Other regions include the various specialized subcortical and cortical areas involved in each sensory and motoric modality. These are typically thought to be the brain regions where the decisions reached by the control areas are implemented. But that does not mean that these regions are themselves home to the selective mechanisms.

Selection occurs instead via the transmission of information between the regions of the frontal-parietal network, and between this network and specific sensory-motor areas. The mechanism of communication that is now widely being considered for this role is the synchronization of oscillatory neural activity through inter-area signals in different frequency bands (Jensen et al., 2014; Kim & Kastner, 2019; Knight, 2007). The higher frequency bands in a local region of sensory cortex appear sensitive to sensory input and oscillate in the gamma range (40-60 Hz) or even higher frequencies. Thus, when attention is captured by stimuli in a bottom-up manner, synchrony in the visual cortex occurs in these higher ranges.

On a longer time scale, neural oscillations in the so-called alpha region (8-12 Hz) in visual sensory areas seem to be intimately tied to optimal target identification and the inhibition of distractors. When alpha oscillations are strong, visual selection is biased away from sensory information and toward internally generated signals; conversely, when alpha oscillations are at their weakest, then sensitivity to sensory signals are at their strongest (Hanslmayr et al., 2011). At oscillatory peaks in the cycle, inhibition prevents neuronal firing in these regions. As inhibition ramps down within a cycle, a set of neuronal representations will activate sequentially according to their respective excitability. This proposal for a mechanism of visual selectivity serves to convert spatially distributed representations in early visual regions to a temporal phase code, creating in effect a to-do list that can be processed sequentially by other communicating brain regions.

When it comes to looking for a mechanism that influences whether these visual sensory regions are tuned to visual input or not, a current proposal is that sensory regions are in communication with the frontal-parietal network using lower frequency theta-band oscillations (3-8 Hz) to manage these longer-distance neural connections (Jensen et al., 2014). These connections help to determine whether the sensory region is responding optimally based on behavioral goals or on the lower-level stimulus properties. One proposal for how this comes about is by using cross-frequency phase-amplitude coupling between higher-order areas and sensory areas. For example, the phase of low-frequency oscillations from frontal-parietal areas is thought to determine the amplitude of high-frequency oscillations in sensory areas during goal directed tasks (e.g. high amplitude of local high-frequency oscillations driven by peak activity in the more global low-frequency oscillations; Kim & Kastner, 2019).

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Regardless of whether these specific mechanisms turn out to be the key to understanding selective attention, the dynamic framework makes it clear that a wide range of interrelated factors determine the selectivity of perception, cognition, and action at any given moment. As such, we should not be surprised that most relationships involving attention and sport are intertwined and run in all directions. For example, within the third section of this manuscript sleep, exercise and personality were each individually linked to attentional processes, but outside the laboratory these factors are likely to interact and influence one another. Lambiase et al. (2014), for instance, found that lower quality sleep in women was associated with worse attentional shifting as measured by trail making B, but, only among women with lower levels of physical activity. Physical activity as such appears to be at least partially protective against the negative ramifications of sleep loss. Furthermore, both sleep quality and exercise adherence are correlated with conscientiousness (Rhodes & Smith, 2006; Williams & Moroz, 2009). Duggan et al. (2014) for instance found that lower conscientiousness associated with worse sleep hygiene, sleep quality, and increased sleepiness, whereas Ludwig et al. (2019) found that planfulness, a quality of conscientiousness that reflects individual differences in mental and cognitive preparatory processes for goal achievement, was positively associated with more frequent visits to a recreation center.

The connection between emotion and attention is also highly intertwined (see Brennan & Enns, 2014, for a review). We attend to stimuli associated with emotional outcomes, but we also attribute emotional significance to stimuli we have recently attended to. Relevant here is research by Mrkva et al. (2019), in which participants first rated the emotional intensity of a set of images, before searching for one of these images as a target in a discrimination task. Participants then rated the emotional intensity of these images once again. Images designated as targets in the discrimination task were now rated as emotionally more intense than they had been initially. The degree of importance given to positive or negative stimuli is also dependent on individual differences. Mathews et al. (2003) had participants complete a Posner cueing task with task-irrelevant neutral and fearful faces presented to the center of gaze. These faces sometimes gazed left and sometimes right, but randomly with respect to target location. Participants with low levels of anxiety had comparable cueing effects for neutral and fearful faces. However, among highly anxious participants, fearful faces led to stronger cueing effects than neutral faces. Individual differences also modulate the relationship between reward and attention, as individuals who score in higher reward-seeking are also more likely to attend to stimuli associated with reward (Hickey et al., 2010b).

The drive toward adaptation found throughout the brain is encapsulated by the dynamic framework (Figure 1D). As we perceive, think, and move in the world, feedback from our experiences and our attempts to interact with the environment are constantly shaping what we consider to be normal (Pezzulo & Cisek, 2016). What we are currently

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experiencing influences what we will selectively attend to and do next. For instance, when engaging in a conversation it is common to indicate that one has finished speaking by gazing directly at the listener (Ho et al., 2015). When we are hungry, our attention will be biased toward food and food-associated stimuli (Mogg et al., 1998; Tapper et al., 2010). Subjective reports of craving for caffeine, alcohol, tobacco and other substances correlate positively with attentional biases toward these items (Field et al., 2004; 2009). And once our hunger or cravings have been satiated, these biases become weaker and other aspects of our current states (e.g., our interests) will be most likely to draw our attention to particular objects and events in the environment.

What are the practical implications of using the dynamic framework to better understand the relations between attention and athletics? As we have reviewed, studies in separate literatures have reported that behavioral practices such as extending the time spent in sleep offers benefit for both attention and sport performance. Within the dynamic framework (Figure 1D), we should expect this relationship to interact with other factors, such as age and personality. This is in line with the National Sleep Foundation recommending different optimal sleep durations depending on age (Hirshkowitz et al., 2015), ranging from 8 to 10 hours for teenagers, 7 to 9 hours for young adults, and 7 to 8 hours for older adults. Furthermore, individuals scoring high on extraversion and conscientiousness appear to be those individuals who experience relatively better sleep quality, while those scoring high on neuroticism tend to report poorer sleep quality (Hintsanen et al., 2014; Stephan et al., 2018). This suggests that a one-size-fits-all sleep exercise regime is unlikely to be ideal. Instead athletes, coaches, and scientists who are interested in maximizing athletic performance via sleep modification may have more success by considering these factors collectively.

Another example demonstrating the multifaceted relationship between attention and sport concerns hydration. As reviewed, research suggests that euhydration benefits both performance on attention-based tasks in the laboratory and athletic performance on the field. When dehydration occurs, however, it may be the consequence of several factors, including environmental restrictions in fluid, thermal stress, behavioral practices such as continual exercise without rehydration, and/or individual choices made as a result of instruction and experience. While having an available supply of water (an environmental intervention) may alleviate some of negative consequences of dehydration (Kaushik et al., 2007), altering behavioral practices may require changes in coaching doctrine, and altering individual choices may require a combination of environmental changes (water availability) and explicit instruction. Pertinent here is that in some sport contexts, dehydration may even be a temporary goal, as when athletes in sports with defined weight classes (e.g. wrestling, boxing, mixed martial arts, rowing) cut weight immediately before a competitive event (Choma et al., 1998). In these contexts, identifying strategies to prevent dehydration may be irrelevant. Instead, under such circumstances understanding the optimal methods

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to quickly recover from dehydration, as well as understanding the long-term effects of dehydration, may be more important.

Perhaps the most important positive consequence of adopting the dynamic framework, in which selective processing is taken to be an outcome rather than a cause, is a shift in perspective that leads to important questions that otherwise might not have been asked. This includes asking, for example, what is the relative strength of the various factors that contribute to optimal athletic performance? The dynamic framework encourages these questions and the testing of these hypotheses as the next steps in attention and sport science.

In concluding this section, it is important to state that while we have discussed broad categories (e.g. behavioral practices) pertinent to developing a fully dynamic framework of attention, and illustrated these categories with specific research streams (e.g. exercise), this is not meant to be an exhaustive list or review. Other factors that could be included, but would greatly increase the length of this review, are environmental ones such as altitude (Bishop & Girard, 2013; Kramer et al., 1993), weather (Castellani & Young, 2012), and the presence and behavior of an audience (Epting et al., 2011; Huguet et al., 1999; Zajonc, 1965). For example, Dube and Tatz (1991) concluded that the presence of an audience improved the play of skilled tennis pupils, at the same time that it impaired the play of less skilled pupils. With similar regard for individual factors, there is important research on internal states such as motivation (Gillet et al., 2009), exhaustion and fatigue (España-Romero et al., 2009; Lohse & Sherwood, 2011; Martin et al., 2016), and the role of anxiety in coping with distraction (Janelle et al., 1992; Williams & Elliott, 1999). Inclusion of these research streams would no doubt help further refine frameworks of attention.

## Conclusion

This review has examined the bi-directional relationship between sport and attention, in addition to important behavioral, environmental, and individual factors that contextualize this relationship. This was done by examining how these factors contribute to performance outcomes in separate literatures for sport and attention. We then used this empirical database to consider how the theoretical understanding of selective attention has evolved in the cognitive sciences over the past five decades. This juxtaposition of data and theory makes it clear to us that research on athletics and attention have much to offer one another, on both a theoretical and practical level. What is discovered in the laboratory of the cognitive scientist can inform best practices and strategies for athletes and coaches in pursuit of athletic excellence. Equally important, what is discovered on the athletic field offers insight into what a complete theory of attention might one day look like.

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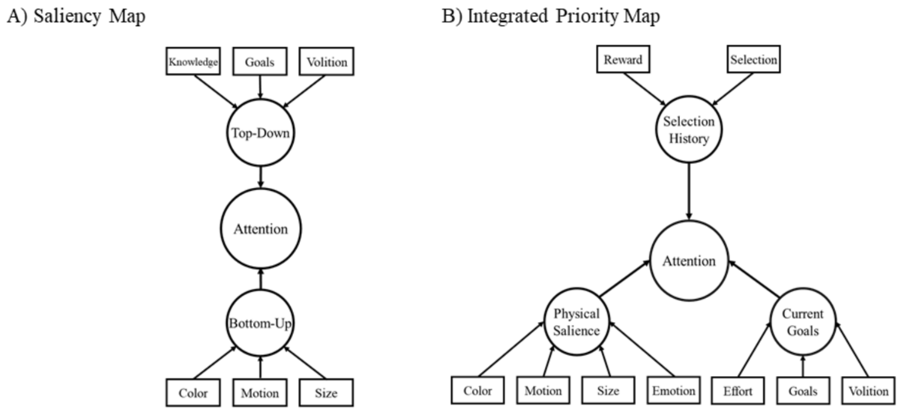


**Figure 1 A-B**

The evolution of attention frameworks

(A) Saliency map. Bottom-up determinants of attention are local differences in simple visual features such as color, motion and edge-orientation. They are considered bottom-up because the human visual system is hard-wired to register these differences as spatial signals for something that deserves closer investigation. Together they form a topographic map indexing the relative priority of spatial regions for further processing (Koch & Ullman, 1985). Top-down determinants of attention include intention, volition, expectation, past experience, and current task goals, which can modulate the saliency map topography so as to bias attention toward specific candidate spatial regions (Bisley & Goldberg, 2010). Sometimes the combined influence of bottom-up and top-down processes is called a priority map. (B) Integrated priority map: Building on the concept of saliency maps, Awh et al. (2012) emphasized that one's history of selection and reward influence attentional priority in a manner that is distinct from either bottom-up or top-down processing. Here bottom-up and top-down processing are referred to as physical salience and current goals, respectively.

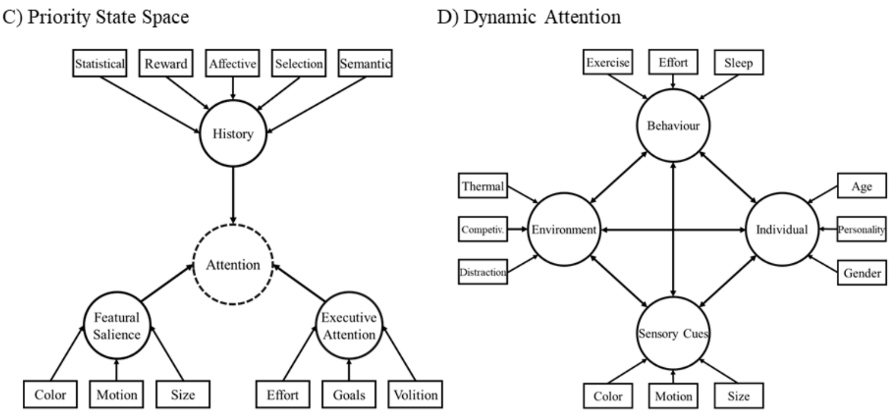


**Figure 1 C-D**

The evolution of attention frameworks

(C) Priority state space: Todd and Manaligod (2018) added to the integrated priority map by including the influence of semantic, statistical, and affective learning to the factor of personal history. Attention is now also enclosed within a dotted circle to reflect a change in metaphor of attention being conceptualized as a state space rather than a map. In addition to this emotion is modelled as influencing attention through affective learning rather than through bottom-up processing. Here bottom-up and top-down processing are referred to as featural salience and executive attention. (D) Dynamic attention: A framework of attention proposed by Ristic and Enns (2015b) and others, where attention is the experiential and behavioral outcome of an entire system of interconnected influences. These include an individual's recent and accumulated experience, their voluntary effort, the environment in which they perceive and act, their long-term traits/individual differences, the sensory cues one is sensitive to, and even ultimately, the behavioral practices one executes and maintains. Each of these factors has a direct influence on what information is privileged by the system at any moment in time.

## Glossary

### Bottom-up processing

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Selective attention that is guided by salient features of the external environment. In vison, these properties include local differences in luminance, color, size, motion, and edge orientation.

**Flanker task**

A measure of the ability to identify a feature of a visual display (e.g., the pointing direction of a central arrow) that may conflict with other spatially adjacent features (e.g., the pointing direction of arrows flanking the central one). This task is taken be a of measure attentional control, since attention must be pushed to the target stimulus despite there being a pull to habitually process and respond to adjacent stimuli.

**Multiple object tracking task**

A measure of the ability to track multiple objects in motion. In a typical version of this task a subset of dispersed items on a computer screen are briefly identified as the targets to be tracked. All items then move independently in random directions for a period of time, before one of the items is probed. Participants indicate whether the probed item is a member of the target set.

**Perimetry task**

An ophthalmological measure of the functional field of view. In a typical perimetry task, the participant is asked to detect a static or moving point of light inside a 180-degree dome. Lights are flashed at various eccentricities in all directions from the center of gaze and the average accuracy of target detection at each location is used to map out the functional field of view.

**Posner cueing task**

A measure of the ability to orient attention to specific regions of space. Spatial orienting can occur in vision because attention is pulled by a local feature difference in the visual field (e.g., flash of light), or because attention is pushed by the observer (e.g., to attend to the right side of a display in expectation of an upcoming target), or through a combination of these two forces.

**Quiet-eye**

A form of attentional control often measured in a sport context where target-eye coordination is critical for successful action. The quiet-eye refers to the interval of time between the onset of a final fixation on a target location (e.g., the front of a basketball rim), and the initiation of a target action (e.g., the onset of a basketball shot). Longer quiet-eye durations are empirically predictive of greater target accuracy. Quiet-eye duration is taken to be a measure of attentional control because attention must be pushed (held) at the target location against the tendency to have fixations be pulled reflexively to other locations in the scene by instinctive exploratory tendencies.

**Saliency**

The magnitude of a local feature contrast within a visual scene. For example, a small region colored red is more salient against a blue background than a pink background.

**Selective attention**

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The processes involved in directing attention to certain features of the environment while other features are ignored. Selective attention can be pulled by bottom-up processes and/or pushed by top-down processes.

**Stop-signal task**

A measure of the ability to cancel an action that has been pre-programmed. In a typical task, participants respond to a target (e.g., reporting if a disc appears on the left or right side of a computer screen), and on a small minority of trials the target is followed by a stop-signal (e.g., a central disc) which indicates that no response should be made. The time interval required for an individual to halt a response when presented with the stop-signal is interpreted as a measure of attentional control, since attention must be pushed to inhibit the habitual response that is made on the majority of the trials.

**Stroop task**

A measure of the ability to identify a feature of a visual stimulus while ignoring other features of that stimulus which may impede identification via habitual or reflexive responding. For example, the traditional Stroop-task involves participants trying to name the ink color of a word (e.g., blue) that spells a color word (e.g., "red"). Naming the ink color is more difficult when the word spells a conflicting color (e.g., "red") than when it spells a congruent color (e.g., "blue"). The difference in these two conditions is taken to be a measure of attentional control, since attention must be pushed to identify ink-color despite a habitual pull to read and recognize printed words.

**Top-down processing**

Selective attention that is guided by the intentions of an individual. In vision, these intentions may be based on prior expectations, knowledge, goals, willingness to expend mental effort, and instruction.

**Trail making test**

A measure of the ability to shift attention in space. Participants must use a pen to rapidly connect spatially dispersed numbers on a piece of paper in ascending order in task A (e.g. 1-2-3), or numbers and letters in alternating-ascending order in task B (e.g. 1-A-2-B-3-C).

**Useful field of view task**

A measure of the ability to distribute attention across space. In a typical task, a target appears among many distractors and at various eccentricities from a central fixation. The participant's accuracy in detecting targets at different eccentricities is interpreted as a measure of attentional breadth.

**Visual search task**

A measure of the ability to shift attention from one region of space to another, by asking participants to identify a pre-designated target embedded in a cluttered display. Pop-out search can occur because attention is pulled to the target by a local feature difference (e.g., unique color), and effortful search can occur when the target and distractor items are very similar to one another and attention must be deliberately pushed to candidate items until the target is found.

**Working memory**

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A memory system used for the storage and manipulation of mental information, in anticipation of having to use that information in the service of an on-going task. One measure commonly used to assess working memory is the backward digit span task, where participants are briefly shown between 3 and 9 digits in succession and their task is to report these digits in reversed order.

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## Notes

**1** There is considerable body of research on the neurophysiological correlates of attention, and much of this research informs behavioral research on attention. The present review, however, is focused on behavioral research and thus how behavioral measures of attention are related to sports performance.

## Información adicional

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