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The Relationship Between Gaze Behavior, Expertise, and Performance: A Systematic Review

Stephanie Brams
KU Leuven

Gal Ziv
The Academic College at Wingate

Oron Levin, Jochim Spitz, and Johan Wagemans
KU Leuven

A. Mark Williams
University of Utah

Werner F. Helsen
KU Leuven

Perceptual-cognitive skills enable an individual to integrate environmental information with existing knowledge to be able to process stimuli and execute appropriate responses on complex tasks. Various underlying processes could explain how perceptual-cognitive skills impact on expert performance, as articulated in three theoretical accounts: (a) the long-term working memory theory, which argues that experts are able to encode and retrieve visual information from long-term working memory more than less experienced counterparts; (b) the information-reduction hypothesis, which suggests that experts can optimize the amount of information processed by selectively allocating their attentional resources to task relevant stimuli and ignore irrelevant stimuli; and (c) the holistic model of image perception, which proposes that experts are able to extract visual information from distal and para-foveal regions, allowing more efficient global-local processing of the scene. In this systematic review, we examine the validity of the aforementioned theories based on gaze features associated with the proposed processes. The information-reduction hypothesis was supported in most studies, except in medicine where the holistic model of image perception garners stronger support. These results indicate that selectively allocating attention toward important task-related information is the most important skill developed in experts across domains, whereas expertise in medicine is reflected more in an extended visual span. Large discrepancies in the outcomes of the papers reviewed suggest that there is not one theory that fits all domains of expertise. The review provides some essential building blocks, however, to help synthesize theoretical concepts across expertise domains.

Public Significance Statement
Perceptual-cognitive skills are linked to superior performance in many professional settings (e.g., radiology, aviation, football). In this systematic review, we show that experts are able to maximize their attention to relevant visual information and optimize performance in specific perceptual-cognitive tasks.

Keywords: medicine, perceptual-cognitive skills, sports, visual search strategy

Perceptual-cognitive skills facilitate the ability to process environmental information and organize and produce movements that are relevant for a successful completion of a complex task (Marteniuk, 1976). Superior perceptual-cognitive skills can result in better anticipation and decision making by optimizing how the visual system is used to extract sufficient information relevant to

Stephanie Brams, Movement Control & Neuroplasticity Research Group, Department of Movement Sciences, KU Leuven; Gal Ziv, Motor Behavior Laboratory, The Academic College at Wingate; Oron Levin and Jochim Spitz, Movement Control & Neuroplasticity Research Group, Department of Movement Sciences, KU Leuven; Johan Wagemans, Laboratory of Experimental Psychology, Department of Brain & Cognition, KU Leuven; A. Mark Williams, Department of Health, Kinesiology, and Recreation, College of Health, University of Utah; Werner F. Helsen, Movement Control & Neuroplasticity Research Group, Department of Movement Sciences, KU Leuven.

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Correspondence concerning this article should be addressed to Stephanie Brams, Movement Control & Neuroplasticity Research Group, Department of Movement Sciences, KU Leuven, Tervuursevest 101, 3000 Leuven, Belgium. E-mail: stephanie.brams@kuleuven.be

task completion (Williams, Ward, Smeeton, & Allen, 2004). For instance, to perform and react correctly, radiologists gather visual information from medical images (Bertram, Helle, Kaakinen, & Svedström, 2013; del Ciello et al., 2017), referees by directly observing players (Spitz, Put, Wagemans, Williams, & Helsen, 2016), and tennis players from the body orientation of an opponent (Williams, Ward, Knowles, & Smeeton, 2002). Moreover, poor visual scanning or inefficient processing of visual input could lead to decision-making errors (del Ciello et al., 2017; Marquard et al., 2011; Mourant & Rockwell, 1972; Shappell et al., 2017).

A key issue relates to the extent to which systematic visual scanning can be considered a marker of expert performance. A systematic scan path relates to a strategy by which different areas of interest (AOI) are inspected in a fixed order, allowing increased coverage of those AOIs (Kok et al., 2016). A clear notion is needed of how visual information is used across different professional settings and which eye-movement characteristics can be used to differentiate between skilled and less-skilled individuals. In this systematic review, we had two main aims. First, we describe how experts across different domains of expertise use perceptual-cognitive skills to achieve superior task performance. Second, we provide a theoretical grounding for the role of these skills in expert performance.

The perceptual-cognitive skills used by experts are generally assessed using speed and accuracy measures across various perceptual-cognitive tasks (Gilis, Helsen, Catteeuw, & Wagemans, 2008; Gobet & Simon, 1996; Helsen & Starkes, 1999; Spitz et al., 2016; Williams et al., 2002). However, in an effort to gain more insight into the psychological processes underlying superior performance, eye movement data are often gathered from participants. In this review, the term *gaze features* is used for the different phenomena that form the basis of some eye-tracking measures relating to fixations, which keep the gaze stable on environmental stimuli, and saccades, which are typically rapid eye movements between one fixation location and another (Komogortsev & Karpov, 2013). Variables such as the number and duration of fixations or the length of saccades are expected to differ between expert and nonexpert performers due to an adapted search strategy (for a meta-analysis, see Gegenfurtner, Lehtinen, & Säljö, 2011). Three main features of the eye-movement patterns measured in experts have been put forward: (a) efficient visual search rate; (b) selective attention allocation; and (c) extended visual span. These different gaze features are characterized by specific eye-movement parameters (see Table 1).

According to Wolfe (2012), efficient visual search is governed by two factors, namely, the ability to guide attention toward relevant cues and the speed of rejecting distractors. Highly efficient searches are those in which attention is guided to the target item immediately, thus making the rest of the scene irrelevant. Wolfe, Cave, and Franzel (1989) introduced this concept in their "guided search" model. This model lies at the basis of *the information-reduction hypothesis* proposed by Haider and Frensch (1999). Eye-movements are expected to show longer durations and more fixations/dwells on relevant areas and shorter durations and less fixations/dwells on distractor areas, resulting in high selective attention allocation (for a meta-analysis, see Gegenfurtner et al., 2011; see Table 1). Distractors containing bottom-up signals that pull attention in the wrong direction can be largely ignored if the observer is guiding attention in a top-down fashion, based on the observer's goals (e.g., Bichot et al., 2005; Martinez-Trujillo, 2011; Schoenfeld et al., 2007). This process can be modulated by experience because the appearance of a target in previous trials makes observers faster and/or more likely to find the same target again. The observer will then be attracted to the same target that was observed earlier, only this time the process will occur more automatically (and unconsciously) than the first time when a pure top-down search was conducted. Attention then becomes guided by the observer in a more implicit-like and automatic manner (Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004).

The implicit automatic guidance evolves with experience based on knowledge of the scene. This guidance is no longer based on properties of the target, but on the structure and content of the rest of the scene, a shift from a *feature attention* model to a *scene guidance* model (Wolfe, 2012). To become an expert searcher in a specific domain, performers need to learn how to let the scene guide attention. For example, in radiology, experts look less at the image than novices, because they know where to look for lung cancer in a chest X-ray (Kundel & La Follette, 1972). Similarly, in chess, an expert player identifies specific pieces on the board more quickly when presented with a structured rather than a random setting (Brockmole, Hambrick, Windisch, & Henderson, 2008). In these cases, features of the targets remain the same, but the structure of the scene tells the expert where to look.

As proposed by *the holistic model of image processing* (Kundel, Nodine, Conant, & Weinstein, 2007), experts are able to extract significant information about the scene with a very brief glimpse (Biederman, Rabinowitz, Glass, & Stacy, 1974). During this brief glimpse, the observer is preattentively processing the scene (i.e., information in the visual field is available before selective visual attention is directed to specific locations; Wolfe & Utochkin, 2018). In the next phase, selective attention will occur. Eye-tracking measures will show a shorter time to initially fixate the relevant area (e.g., lung nodule), because they know where to look for the target, and longer saccade amplitudes, reflecting an extended visual span that allows global scene processing (Gegenfurtner et al., 2011; see Table 1). In the postattentive phase, attention

Table 1
Overview of Theories, Gaze Features, and Eye-Movement Characteristics

Theory	Gaze features	Eye-movement characteristics
Long-term working memory theory	Efficient visual search rate	Average number of fixations/dwells; fixation durations/dwell times (irrespective of location)
Information-reduction hypothesis	Selective attention allocation	Average number of fixations/dwells; fixation duration/dwell times on AOI
Holistic model of image perception	Extended visual span	Latency of first fixation on AOI; saccade amplitude; para-foveal information processing

is moved to specific locations and more subtle perceptual distinctions will be recognized (Wolfe, Klempen, & Dahlen, 2000; Yeshurun & Carrasco, 1999).

This selective attention originates from endogenous internal attention, meaning that attention is guided by the information stored in the long-term memory, which is gathered there based on relevant experience. These memories can be rapidly retrieved in specific scenes and strongly influence what we come to perceive, as proposed by *the long-term working memory theory* (Ericsson & Kintsch, 1995). Specifically, essential information is ready and stored in the long-term memory because of repeated exposures as a consequence of experience. According to the long-term working memory theory, our working memory can extract the needed information for the completion of the task at hand. The ability to quickly retrieve the information from the long-term memory results in a fluent output of essential specific task information. Because of the rapid availability of essential information, eye-tracking measures are expected to show shorter and fewer fixations irrespective of location (Gegenfurtner et al., 2011; see: Table 1). According to Rayner's (1998) assumption, these eye-tracking measures represent a more efficient visual search rate.

The role of memory in visual search can be seen in the analysis of visual scanning patterns, more specifically, in the order in which scene elements are inspected. It appears that better memory for a specific scene helps to memorize which areas have already been inspected, resulting in a more efficient search (Võ & Wolfe, 2012; Wolfe, Vo, Evans, & Greene, 2011). *Inhibition of return* was proposed as the mechanism by which rejected distractors were tagged during search to prevent reinspection of these areas (Klein, 1988; Posner & Cohen, 1984). Pure systematic scanning patterns never return to the same area. The findings from multiple domains of expertise show that experts have more systematic scanning patterns compared with nonexperts. Previously, researchers have identified a link between systematic scanning and a higher detection rate (del Ciello et al., 2017; Kok et al., 2016) as well as between systematic scanning and a higher level of expertise (Augustyniak & Tadeusiewicz, 2006; Leong, Nicolaou, Emery, Darzi, & Yang, 2007; Li, Shi, Pelz, Alm, & Haake, 2016). Furthermore, it has been shown that adapting systematic scan patterns through training can reduce detection errors and improve diagnostic performance among radiologists (Stockman, 2016).

The aforementioned theories and models suggest that the gaze strategies and eye-movement characteristics observed in experts are not mutually exclusive and their presence and interrelationships may vary. These variations could partly be explained by task characteristics as well as the level of expertise and/or performance within specific domains of expertise (Augustyniak & Tadeusiewicz, 2006; Crespi et al., 2012; Kok et al., 2016; Leong et al., 2007).

In this systematic review, we focus on the three theories discussed in the meta-analysis by Gegenfurtner et al. (2011): (a) the long-term working memory theory; (b) the information-reduction hypothesis; and (c) the holistic model of image processing. These theories highlight the important aspects of attention that might underpin perceptual-cognitive skills in experts. The meta-analysis by Gegenfurtner et al. (2011) suggests that experts generally tend to adopt the long-term working memory and/or information-reduction strategies more than the holistic model of image perception. In Table 1 different gaze features that can provide evidence for each theory are summarized. Eye-tracking measures addressing these gaze features possibly provide us information about the empirical support of a particular theory in a specific expertise-domain (Gegenfurtner et al., 2011). However, little is known about the number of relevant eye-movement characteristics that were measured for each theory. Interpretation bias might occur as a consequence of this fact. For example, if studies in one domain mostly measured eye-movement characteristics supporting the holistic model of image perception and very few gaze features that speak to the other theories, it will be difficult to assess the contribution of the other theories to this domain. Furthermore, if this is an extensively studied domain, this theory might be put forward as more important across the board, which may be unjustified as well.

Current literature lacks clear insights into the interplay between gaze features and superior performance of perceptual-cognitive tasks in experts. In this systematic review, therefore, gaze features and visual scan patterns were examined as the signature mechanisms underlying superior perceptual-cognitive performance in experts. We address three specific research questions.

1. Which types of eye-movement characteristics best predict expertise and what is their relation to superior performance on perceptual-cognitive tasks?

2. To what extent does systematic scanning predict expertise and superior performance on perceptual-cognitive tasks?

3. Can gaze features and related theories be generalized across different domains of expertise and tasks?

We hypothesize that eye-movement characteristics as measured during performance on perceptual-cognitive tasks differ between experts and nonexperts, as well as across different types of tasks within each domain of expertise.

Method

Literature Search Strategy

The data in this review were collected on the 19th of December 2018 through a systematic search of four electronic databases: PubMed; SPORTDiscus; Web of Science; and Embase. The search terms were synonyms of the following three categories: *eye movements*; *perceptual-cognitive* and *decision making*; and *expertise*. The different categories were combined with the Boolean operator AND, terms within the same category with OR (see Table 2). Only peer-reviewed articles published in English were included. Also, when a research article was an expansion of previous conducted research, data from the most recent article were selected.

Selection Criteria

A Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart was used to provide an overview of the studies (see Figure 1). The search retrieved a total of 16,083 likely relevant articles, of which 2,527 duplicates were removed. The title and abstract of all 13,556 remaining articles were screened by the lead author and cases of doubt were discussed by

Table 2
Search Strategy

Databases	Entered search terms	Mesh and Emtree terms
PubMed (title and abstract)	Category 1: eye movement* OR ocular movement* OR ocular focus* OR eye focus* OR smooth pursuit* OR saccad* OR visual search* OR gaze OR gazing OR eye tracking OR systematic viewing OR visual scan pattern* OR eye scan pattern* OR visual perception* OR visual field*	Pubmed Mesh terms: "Eye movements"; "fixation, ocular"; "pursuit, smooth"; "saccades"; "visual perception"; "professional competence"; "occupational groups"; "simulation training"; "athletic performance"; "decision making"; "attention"; "clinical decision-making"; "task performance and analysis"; "cognition"; "pattern recognition, visual"; "anticipation, psychological"
Embase (title and abstract)	AND Category 2: Professional Competenc* OR professional skill* OR clinical Competenc* OR clinical skill* OR expert* OR Occupational Group* OR athletic performance* OR sports performance* OR expert performance* OR superior performance* OR perceptual-cognitive expertise OR elite perform* OR perceptual-cognitive skill*	Embase Emtree terms: "eye movement"; "eye fixation"; "vision"; "professional competence"; "named groups by occupation"; "simulation training"; "athletic performance"; "decision making"; "attention"; "task performance"; "cognition"; "pattern recognition"; "anticipation"
SPORTDiscus (title and abstract)	AND Category 3:	
Web of Science (topic)	decision making* OR attention OR response inhibition OR clinical decision-making OR clinical decision making OR medical decision-making OR medical decision making OR cognitive performance OR cognition OR pattern recognition OR anticipation	

coauthors. Doubtful decisions for inclusion/exclusion were resolved by the senior coauthor. After screening by title and/or abstract, 13,401 articles were excluded according to following criteria: (a) the participants were not healthy, or were not active experts; (b) during perceptual-cognitive task completion no eye-movement characteristics were measured; (c) the main focus of the study was not on perceptual-cognitive performance in specific tasks; (d) the article did not report any accuracy and/or response time scores; (e) the article did not focus on expertise or included only groups of specialists with no reference group of novices; and (f) the main focus of the article was on technical aspects or experimental protocols. The remaining 155 articles were evaluated as potentially relevant papers. After screening the full-text of those articles, using the above-mentioned exclusion criteria, another 82 articles were excluded leaving 73 papers. The specific reasons for exclusion are described in Figure 1.

Analysis

In addition to qualitative analysis, effect sizes for the eye-movement measures that predict expertise were reported when available. All effect size data are available at the following link: https://osf.io/3hp9b/?view_only=316ba9503f4c4846878703d3901a1963. When effects sizes were not reported, we used other published statistics to calculate them, if possible (Lenhard & Lenhard, 2016). Second, all types of effect sizes were transformed to Cohen's *d* values, using the online calculator provided by Lenhard and Lenhard (2016). For the evaluation of the effect sizes, we relied on Cohen's (1988) commonly used guidelines: .20 (small), .50 (medium), .80 (large). For each gaze feature the weighted mean effect size and 95% confidence interval (CI) were calculated separately for each expertise domain, using the Metafor package for R (R Core Team, 2014). For calculation of the weighted mean effect sizes, we used the restricted maximum-likelihood (REML) method, because of the diversity of study characteristics (e.g., eye-tracking measures conducted, tasks, expertise domains). To examine whether there was publication bias we used the Egger test (a test for funnel plot asymmetry; Egger, Davey Smith, Schneider, & Minder, 1997), the trim and fill procedure (a procedure that corrects funnel plot asymmetry; Duval & Tweedie, 2000a, 2000b) and the fail-safe test (a test that examines how many unpublished studies needed with negative results to change the conclusion of the current results; Rosenthal, 1979). These analyses were conducted for gaze features that were reported in at least 10 studies within the same domain of expertise (i.e., in sports: the fixation duration, number of fixations, number of fixation locations, and fixation duration on AOI; Higgins & Green, 2011).

Results

Included Studies and Reported Outcome Measures

From the 73 studies included, gaze features were extracted from the eye-movement characteristics in experts and categorized according to the three theories previously outlined. The perceptual-cognitive tasks across the different expertise domains were further classified either as optimizing (demanding accurate response from participants), maximizing (demanding rapid response), or optimizing-maximizing (demanding both accurate and rapid responses; see Steiner, 1972). In addition, tasks were classified as nonexplicit if no demands on accuracy and/or response time were made. The outcomes were summarized separately for the 36 studies in sport-related domains, the 19 studies in medicine-related domains, and the 18 studies in other domains. Sample characteristics and the specific domain of expertise of all studies as well as

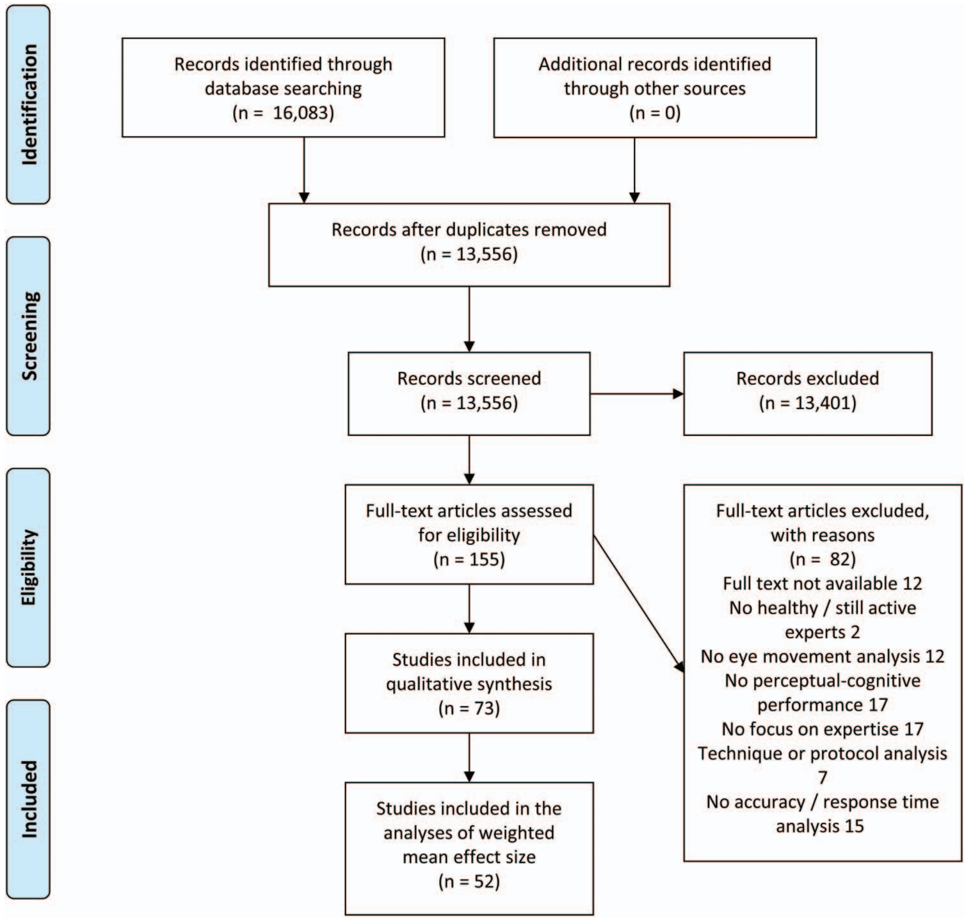

Figure 1. PRISMA flowchart showing the search results and exclusion criteria. See the online article for the color version of this figure.

specific task characteristics are provided in the following two sections. Summaries of the reviewed studies are presented in Tables 3, 4, and 5 for sports, medicine, and other domains, respectively. Tables 6, 7, and 8 provide more details regarding the types of tasks, expertise domains, task outcome, and gaze characteristics for sports, medicine, and other domains, respectively.

Sample Characteristics and Domains of Expertise

The sample sizes across the reviewed studies varied from four (Krupinski, Chao, Hofmann-Wellenhof, Morrison, & Curiel-Lewandrowski, 2014) to 69 (Page, Bates, Long, Dawes, & Tipton, 2011) participants, and the reported age range was 14 to 70 years. In 51 of the 73 studies included, comparisons were made between experts and novices or experienced (skilled) and less experienced (less skilled) individuals. In 21 studies, comparisons were made between three levels of expertise (i.e., novices, intermediates, and experts).

The expertise groups in sports-related domains were differentiated by the experience period (in years), performance level (elite vs. subelite or engagement in top-division vs. lower-division clubs), and/or engagement/training time (hours/weeks). For medicine-related domains, expertise groups were selected based on years of experience, training level and rank (e.g., specialists vs. residents/students), or number of cases treated by the experts (Mallett et al., 2014). In other domains, experience (e.g., years, months, hours practicing the skill) was used as the main measure for expertise. In chess, specific measures were used (e.g., the Elo rating system or Chess Federation of Canada ranking). Altogether, 10 of the 73 included studies followed the 10-years or 10,000 hr-of-practice rule of Ericsson, Krampe, and Tesch-Römer (1993) as a selection standard for an expert group (see Tables 3–5). The most frequently studied subdomains in sports were soccer and basketball (see Table 3). The main subdomain in medicine was radiology (see Table 4).

Perceptual-Cognitive Tasks and Reported Outcome Measures

Sports. For the main part, perceptual-cognitive tasks in sports have involved a variety of anticipation tasks. Anticipation tasks are those that require participants to foresee what comes next. In some of these studies, an occlusion task was employed where the whole scene or certain parts of the scene are covered at select time points in the action (e.g., Alder, Ford, Causer, & Williams, 2014; Mori et al., 2013; Williams et al., 2002). Other perceptual-cognitive tasks

Table 3
Search Results for Studies in Sport-Related Domains

Study	Sport	Participants	Perceptual-cognitive task	Performance		Differences in gaze behavior as function of expertise	Expert's visual search strategy
				Response time	Accuracy		
Alder, Ford, Causer, and Williams (2014)	Badminton	Experts: $n = 8$; International level players with more than 10 y of experience & 20h/week of training Novices: $n = 8$; No experience	Temporal occlusion on badminton serves (physically carry out a return shot).	NA	Higher in experts.	Both groups fixated the racket significantly more on correct trials compared to incorrect trials. But experts fixated on the racket in more correct trials compared to all other regions of interests. Novices fixated more on the shuttle as compared to experts. The number of correct trials in which the shuttle was fixated was significantly lower than racket or wrist.	*Selective attention allocation*
Campbell et al. (2014)	Golf	Professionals: $n = 17$; No handicap Elite amateurs: $n = 14$; +1.14 handicap Club amateurs: $n = 14$; +10.29 handicap	Green-reading slope perception from 6 different green-reading positions.	NA	Overall higher in professionals but no significant group differences.	Less skilled golfers (club armatures (CA)-level) displayed significantly more fixations and shorter fixation durations than the other two groups in three of the six positions. No significant effect of green-reading positions and expertise on specific regions of interest fixated.	*Selective attention allocation*
Canal-Bruland, Lotz, Hagemann, Schorer, and Strauss (2011)	Soccer	Skilled: $n = 21$; Semiprofessional Less skilled: $n = 21$; Recreational Controls: $n = 14$; No experience	Change detection on overview images of soccer situations.	No significant group differences.	NA	Skilled and less skilled soccer players used fewer fixations than controls. Fixation duration was longer in skilled soccer players, compared to controls. The fixation durations of less skilled players did not differ from the other two groups. No group differences in visual span.	*Slower visual search rate*

(*table continues*)

Table 3 (*continued*)

Study	Sport	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Casanova et al. (2013)	Soccer	High-level (n = 8) and Low-level (n = 8) professional or semiprofessional	Anticipation of possible soccer actions (pass, shot at goal; retain position) during offense sequences.	NA	Higher in high-level players.	High-level players used more fixations of shorter duration to more locations at the beginning of each half; towards the end, they used fewer fixations of longer duration to fewer locations. Low-level players used longer fixations at the beginning of each half compared to later in the half, the average duration of fixations for the high-level participants did not differ across all sessions. No group effect on fixation locations.	*Adapted visual search rate*
Crespi et al. (2012)	Billiard	Experts: n = 21; National professional to third category Novices: n = 21; Engagement < one a month	Anticipation of ball trajectory through an occlusion point.	Shorter in experts.	No significant group differences. Novices falsely flagged more events as offside in error and experts missed more offside events	Novices distributed the gaze over a wider area than experts. Experts' fixations were more clustered on a few bouncing points. Novices extrapolated the trajectory of the ball beyond the occlusion point.	*Selective attention allocation*
Del Campo et al. (2018)	Refereeing	Experts: n = 11 assistant referees; Novices: n = 11 football players	Decision-making (offside judging)	NA	Higher in experts	Experts: higher number of fixations and greater percentage viewing time on the last defender. Novices: fixated for longer on areas of no interest.	*Selective attention allocation*
Flessas et al. (2015)	Rhythmic gymnastics (RG)	Experts: n = 10; International level judges Intermediates: n = 10; National level judges Novices: n = 10; Did not judge in official events	Error detection task (Judgement from video clips).	NA	Higher in experts. No differences between intermediates and novices.	Overall, shorter dwells on errors in experts than in other groups. Longer dwells times for reported errors than non-reported errors in intermediates and novices whereas experts showed similar dwells times for all errors. More time of eyes spent off the screen in experts and Intermediates than in novices.	*Selective attention allocation*

(*table continues*)

Table 3 (*continued*)

Study	Sport	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Gorman, Abernethy, and Farrow (2013)	Basketball	Experts: n = 17; 10.3y (±3.36) experience Novices: n = 17; .90y (±1.51) experience	Recall locations of players from game clips.	NA	Higher in experts for attacking but not defensive pattern elements	Both groups spent a greater percentage of time fixating the attacking and defending pattern elements in the attack-only and defense-only conditions, respectively. No skill-related differences for fixation time on ROIs.	*Selective attention allocation*
Gorman, Abernethy, and Farrow (2015)	Basketball	Experts: n = 16; 10.3y (±5.11) experience Novices: n = 16; .40y (±1.14) experience	Recall locations of players and a decision-making task (indicate the best possible option that the ball carrier should execute) on static video and moving video displays.	NA	Higher in experts (both tasks).	No skill-related differences for number of fixations and fixation durations on ROIs. Higher percentage of total viewing time on attacking players in the decision-making task compared to the recall task. Experts used longer viewing times on the attacking player second closest to the ball carrier whereas novices used longer viewing times on the defending player guarding the ball carrier.	*Selective attention allocation*
Hagemann et al. (2010)	Fencing	Experts: n = 15; top-level champions Advanced: n = 15; regional-level competitions Novices: n = 15; no prior experience	Anticipation: temporally or spatially occluded and cued fencing attacks on a computer screen (predict the target region of the attacks).	NA	Higher in experts and advanced in both occlusion tasks. No group differences for the cuing tasks.	Experts fixated longer on the upper trunk region than the other groups. Novices fixated longer on the upper legs than the other groups. No changes in gaze behavior during the cuing tasks. No group differences in visual search rate. No group differences in eye-movement characteristics during the spatial occlusion or cuing conditions	*Selective attention allocation*
Hancock & Ste-Marie (2013)	Ice-hockey	Higher-level referees: n = 15; 12.3 y of experience Lower-level referees: n = 15: 3.3 y of experience	Decision-making (penalty/no-penalty) from game clips.	NA	Higher in higher-level referees.	No significant skill-related differences for average number of fixations and average fixation durations. No reports on other gaze characteristics.	*NA*

(*table continues*)

Table 3 (*continued*)

Study	Sport	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Laurent, Ward, Williams, and Ripoll (2006)	Basketball	Experiment 1 Experts: $n = 7$; national level players. Novices: $n = 7$; no competitive experience	Pattern recognition task. schematic configurations: coherent (players organized in logic positions) or non-coherent (no logic positions).	NA	Higher in experts in coherent configuration. Only in experts: higher accuracy in coherent than non-coherent configurations.	Experts made fewer fixations than novices but did not globally differ on fixation durations. Decreased number of fixations in novices in non-coherent configurations. No significant effect of coherence on number of fixations and fixation durations in experts.	*Slower visual search rate.*
		Experiment 2 Experts: $n = 8$; Novices: $n = 9$; levels of expertise as in Experiment 1	Same procedure as in experiment 1 with rotated viewpoint.	NA	No expertise effects.	Experts used more fixations in the non-coherent and rotated condition, compared to the coherent and rotated condition. Longer mean fixation duration when the target was rotated. No group differences in fixation duration.	
Lex, Essig, Knoblauch, and Schack (2015)	Soccer	Experienced players: $n = 10$; Specific soccer training received at fourth up to first league Less experienced players: $n = 10$; Specific training received at club-level up to seventh league.	Decisions on team-specific four tactics (counter-attack, change sides, back to defense, pressing) within a two-choice reaction time task on match situations projected on a PC screen.	Shorter in experts.	NA	Experienced players made fewer fixations and observed fewer pixels within each match situation than less experienced players.	*Slower visual search rate*
Manzanares, Menayo, and Segado (2017)	Sailing	Experts: $n = 10$ top junior sailors; Novices: $n = 10$ bottom ranking	Anticipation (Be as close to the start-line as possible before the race starts)	NA	Top juniors are closer to the start line	The top juniors used more fixations in total and fixated more on relevant locations and less on irrelevant locations compared with the bottom-ranking group.	*Faster visual search rate and selective attention allocation*
McRobert, Williams, Ward, and Eccles (2009)	Cricket	Skilled: $n = 10$; professionals batters Less skilled: $n = 10$; recreational-level batters	Anticipation task: play a stroke that would intercept the ball's flight path.	NA	Higher in skilled batters.	No significant main effect for group for mean fixation duration and number of fixations. More fixation time on ball-hand location compared to other fixation locations. Less skilled batters spent more time fixating the ball-hand and other locations compared to the skilled batters who spent more time viewing the bowling arm, head–shoulder, trunk–hips, and predicted ball release area.	*Selective attention allocation*

(*table continues*)

Table 3 (*continued*)

Study	Sport	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Milazzo, Farrow, Ruffault, and Fournier (2016)	Karate	Experts: n = 14; 15.9y ± 2.2; International-level. Novices: n = 14; 1.6y ± .7; recreational	Decisions about various attacks in different fight scenarios against a standardized expert opponent.	Shorter in experts.	Higher in experts.	Experts made fewer fixations of longer duration and fixated on fewer locations, compared to novices. Experts spent significantly more time fixating on the head and the torso of the opponent compared with Novices. Decision accuracy was positively related to the mean fixation duration, knowledge and negatively related to the mean number of visual fixations, and the mean number of fixation locations	*Selective attention allocation with slower visual search rate*
Mori & Shimada (2013)	Rugby	Experts: n = 10; Collegiate rugby players. Novices: n = 10; No experience	Anticipation task: predict direction change of a running opponent from video clips.	Shorter in experts.	No group effect	Experts fixated more on hips and legs whereas novices spend more viewing time on the chest. Viewing time at each fixation location was affected by type of action but no interaction between fixation location, action, and group.	*Selective attention allocation*
North, Williams, Hodges, Ward, and Ericsson (2009)	Soccer	Skilled: n = 11; professionals at Premier League club; play time per week = 11.3h ± 4.8	Anticipation task: predict the ball's destination from high structured or low-structured offensive (occluded clips)	NA	Higher in skilled players.	Skilled participants fixated more locations per second than less skilled players irrespective of task. Skilled participants did not differ in the number of fixation transitions across both tasks. Less skilled participants showed fewer transitions in recognition compared to anticipation task.	*Faster visual search rate*
		Less skilled: n = 15; recreational-level; play time per week = 1.0h ± 1.2	Recognition task: recognize images from anticipation task indicating "Yes" or "No".	No group effect	Higher in skilled players. (filmed > PLD)	No group differences in number of fixations, fixation durations, and % viewing time per location.	

(*table continues*)

Table 3 (*continued*)

Study	Sport	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Núñez et al. (2009)	Soccer	Experts: $n = 10$; Minimum 10y and 10,000h. Novices: $n = 10$; armatures.	Anticipation task: step on a plate on the opposite side of the goalkeeper's movement (clip of a defending goalkeeper).	Faster in experts.	No group effect.	Both all players focused their vision mainly on the upper half of the goalkeeper body in the pre-test. Both Experts and Novices in the information group focused their vision mainly on knees and upper section of lower extremity in the post-test.	*Adapted selective attention allocation (irrespective of experience)*
Piras, Lobietti, and Squatrito (2014)	Volleyball	Experts: $n = 15$; professional league players. Novices: Not involved regularly	Anticipation task: determine whether the offensive action in the stimulus would come forward or backward of the setter.	Longer in experts for correct responses and longer in novices for incorrect responses.	Experts showed more correct responses than Novices on both forward and backward actions.	Experts' performance and correct responses were both associated with a lower number of fixations and shorter fixation durations. Correlation observed between fixation durations and number of correct responses in Novices (irrespective of response time).	*Slower visual search rate*
Piras, Raffi, Perazzolo, Malagoli Lanzoni, and Squatrito (2017)	Table tennis	Experts: $n = 10$; Professional level players. Novices: $n = 15$; Students.	Anticipation task (choice reaction): Participant had to predict, as soon as possible, in which hemi-field (left or right) the ball would have been returned.	Shorter in experts.	Higher in experts.	Experts: fewer fixations of longer durations compared to novices and more and longer fixation durations on hand-racket during forehand and trunk during backhand. Experts made more saccades on hand-racket during forehand and on trunk during backhand in comparison to novices who made more saccades when they fixated on ball area during forehand stroke. The experts made more microsaccades fixating on hand-racket during forehand and on trunk during backhand with respect to novices, who made more microsaccades when they fixated head area in both stroke techniques. In experts and novices, the distribution of microsaccade direction was uneven during fixations on ball and on hand-racket areas.	*Selective attention allocation and slower visual search rate*

(*table continues*)

Table 3 (*continued*)

Study	Sport	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Pizzera, Möller, and Plessner (2018)	Gymnastic judgement	35 gymnastic judges divided over two criteria: Experience and Specific Motor Experience (SME: $n = 18$; no SME: $n = 17$ → equal spread of experience)	Error detection task: Judge handsprings according to the criteria of the Fédération International de Gymnastique (Participants receive deductions of different severity with respect to form errors or other aspects)	NA	Higher in high level judges (HLJ) compared to low level Judges (LLJ). No difference between SME and no SME judges	HLJ: More fixations on the gymnast during the whole skill and landing phase compared to LLJ No difference in fixation duration between HLJ and LLJ Judges with SME: more and longer fixations on the gymnast and on the legs during the whole skill compared to judges without SME.	*Selective attention allocation*
Ripoll, Kerlirzin, Stein, and Reine (1995)	Boxing	6 experts (National team); 6 intermediates (train once a week); 6 novices (more than a year practice, no competition)	Problem-solving task: manipulate joystick showing the appropriate response behavior in a match situation when watching a movie of an opponent.	No group difference	Higher in experts (only in complex situations	Experts used fewer fixations than the other groups. All participants fixated more on the upper part of the body. The lower body was not fixated by experts. Experts fixated mainly and longer on the head, whereas the other participants fixated mainly and longer on the arm/fist. Experts used a circular scan path around the head and the arm/fist. Novices' scan path was less concentrated on the upper body.	*Slower visual search and selective attention allocation*
Roca, Ford, McRobert, and Williams (2013)	Soccer	Skilled: $n = 12$; professionals/ semiprofessional-level players. Less skilled: $n = 12$; armature or recitative level players.	Anticipation task: predict the next action of the player in possession of the ball (shot at goal or continued dribbling the ball) on life-size video sequences.	NA	Higher in skilled participants.	Skilled players made more fixations of shorter durations than less skilled players. Skilled players used more fixations of shorter duration and toward greater number of locations when interacting with the far task compared with the near task condition. No differences in fixation locations and average fixation durations between "far" and "near" task conditions for the less skilled players.	*Faster and adapted visual search rate*

(*table continues*)

Table 3 (*continued*)

Study	Sport	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Ryu et al. (2015)	Basketball	Skilled: $n = 37$; guards in the top tier of their university league. Less skilled: $n = 37$; recitative level players.	Decision-making: which player was best placed to receive a pass in clips with different viewing conditions (clear, blurred, opaque central or peripheral vision).	No group difference	Higher in skilled players even when information was only available to central or peripheral vision	Both central and peripheral blur increased the fixation duration and this effect was more pronounced in skilled than in less skilled players (albeit no significant group differences were found). With central blur the skilled participants used longer fixations than the less skilled participants did. Viewing times on specific AOIs were not affected by task condition or skill level.	*Visual span*
Savelsbergh, Williams, Van der Kamp, and Ward (2002)	Soccer	Experts: $n = 7$; semi-professional goalkeepers. Novices: $n = 7$; armature or recitative goalkeepers.	Anticipation task: disguise the intended destination of the penalty kick from clips.	No group difference	Higher in experts.	Expert goalkeepers used fewer fixations of longer duration than novices. Experts fixated on significantly fewer areas per trial than Novices. Novices spent more time fixating on the trunk, arm and hip regions than experts (who fixate more on head) as penalty kick evolved. Experts fixated more on kicking leg, non-kicking leg, and ball regions as the penalty kick unfolded as compared to novices who spent progressively more time on unclassified regions.	*Slower visual search rate and selective attention allocation*
Schnyder et al. (2014)	Refereeing	Expert assistant referees (11.3 ± 3.1 years experience): $n = 6$; near-expert assistant referees: $n = 3$ (7.3 ± 4.0 years experience)	Decision-making (judging offside)	NA	Higher in expert assistant referees	There was no difference between expert and near experts in fixation locations. Not significant, but a trend showed a smaller total number of fixations, a smaller number of fixations up to the decisive pass, earlier stabilization of the final fixation, longer final fixations, and later offset of the final fixation for correct than for incorrect decisions.	*Selective attention allocation & slower visual search rate (performance related)*

(*table continues*)

Table 3 (*continued*)

Study	Sport	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Spitz, Put, Wagemans, Williams, and Helsen (2016)	Soccer	Elite referees: $n = 39$; Active at first and second highest division of professional football. Sub-elite referees: $n = 19$; Active at lower competitive levels with no professional experience.	Decision-making: assess foul play situations in open play and corner kicks from video clips and make correct technical (no foul; (in)direct free kick or penalty) and disciplinary (no card; yellow; or red) decisions.	NA	Higher in elite referees.	No group differences in the total number of fixations and fixation durations. In open play situations, Elite referees spent more time fixating the contact zone of the attacker and less time fixating the non-contact zone of the attacker. No main effect of group for fixation location was observed in corner kicks albeit Elite referees tended to spend more time fixating on contact zones whereas Sub-elite referees tended to spend more time fixating on non-contact zones (irrespective of the player's role).	*Selective attention allocation*
Takeuchi & Inomata (2009)	Baseball	Experts: $n = 7$; Members of the university baseball team Novices: $n = 7$; No experience in baseball	Decision-making: push a button on a baseball bat when to swing the bat in clips of a pitcher pitching a ball.	Shorter in experts.	Higher in experts.	Experts fixated on more areas than novices. Experts fixated exclusively on the pitcher's arm and release point of the ball at the final phase of the pitch whereas novices fixated mainly on the head and face throughout the whole pitch.	*Selective attention allocation & faster visual search rate*
Uchida, Mizuguchi, Honda, and Kanosue (2014)	Basketball	Experts: $n = 8$; Top league of collegiate basketball. Novices: $n = 8$; No experience.	Anticipation task: indicate verbally whether free throw attempt of player in clip would be a success or a failure (replay speeds: slow, normal, fast).	NA	Higher in experts only in normal speed.	Experts viewed the shooters' upper and lower body as well as shot trajectory whereas the novices mostly focused on shot trajectory. Experts made fewer fixations on shot trajectory for fast-motion replay speed whereas search strategy of novices was similar for all reply speeds.	*Adapted visual search strategy in experts and attention allocation*

(*table continues*)

Table 3 (*continued*)

Study	Sport	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Vaeyens, Lenoir, Williams, and Philippaerts (2007)	Soccer	Youth soccer players (n = 40) with the highest (n = 20) and lowest (n = 20) rankings according to their numbers of successful decision-makings.	Decision-making: respond to an imagined pass from a team-mate in clips.	Shorter in successful players.	Group differences were observed across all viewing conditions except of the 2-vs. 1 condition	Successful players used a higher number of fixations and alternated their gaze more frequently between the player in possession of the ball and other areas than less successful counterparts. Successful players spent more time fixating on the player in possession of the ball	*Faster visual search and selective attention allocation*
Vansteenkiste, Vaeyens, Zeuwts, Philippaerts, and Lenoir (2014)	Volleyball	Experts: n = 10; (first division). Intermediate: n = 10; (third-fifth division). Novices: n = 17; Students	Anticipation task: react to the pass direction by moving into the same direction as in the clip.	Longer in novices.	Higher in experts.	Experts looked more to the receiver than novices before ball-receiver contact and had a higher percentage of looking towards the attackers than novices and intermediates after the pass from setter to attacker. Experts also use more inter-event fixations towards the moment of the pass than novices and intermediates	*Selective attention allocation and visual span*
Williams, Davids, Burwitz, and Williams (1994)	Soccer	15 experienced and 15 inexperienced soccer players	Anticipation task: Anticipate pass destination from filmed 11 × 11 soccer situations.	Shorter in experts	Higher in experts	Inexperienced players fixated more frequently on the ball and the player passing the ball, whereas experienced players fixation on peripheral aspects of the display (position and movements of other players). Experts fixated on more locations and used more fixations of a shorter duration.	*Selective attention allocation, faster visual search rate and visual span*
Williams and Davids (1998)	Soccer	12 experienced and 12 less experienced soccer players	Anticipation task: movement response to offensive filmed sequences	Shorter in experts	Higher in experts	No difference in search strategy between groups in 3 × 3 situations. In 1 × 1 situations, experienced players had a faster search rate (more fixations of shorter duration). In these situations, experts also fixated more on the hip region compared to the other group.	*Faster visual search rate and selective attention allocation*

(*table continues*)

Table 3 (*continued*)

Study	Sport	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Williams, Ward, Knowles, and Smeeton (2002)	Tennis	Experts: $n = 8$; skilled players (average of 500 matches) Novices: $n = 8$; recreational	Anticipation task: respond to a filmed tennis stroke by taking a step to one of four pressure sensitive pads.	Shorter in skilled players.	No group differences.	Skilled players fixated more on the trunk–hip region compared to other AOIs whereas less skilled participants spent more time viewing the racket. Skilled players used more successive fixations within and between the head–shoulder and trunk–hip regions whereas less skilled players alternated their gaze between racket and ball areas. No group differences in search rate.	*Selective attention allocation*
Wu et al. (2013)[a]	Basketball	Experts: $n = 15$; Skilled players (national second-level) Novices: $n = 15$; No experience.	Anticipation task: response on free basket throw sequences from clips (in and out MRI)	NA	Higher in experts in the 3 and 6 pictures conditions.	No group differences in fixation durations, however Experts made fewer fixations and fixated on fewer AOIs than Novices. Expert first paid attention to the player's arm and wrist, then followed the flying route of the ball, finally focused on the basket. Novices followed the same fixation order but were less consistent in the location of their fixations	*Slower visual search rate, selective attention allocation and systematic search patterns.*

Note. Number of participants per group (*n*) is indicated per each experience level according to the study. The experience level is indicated as the average number of years (y), months (m), weeks (w), hours of practice/competition or level of competition (e.g., international, national, regional). If response time is measured, the outcome for more experienced compared with less experienced counterparts is indicated. This is either faster-lower or the same. If an accuracy outcome is measured, the outcome for more experienced compared with less experienced counterparts is indicated. This is either higher or lower or the same. If the essential measures were not reported, NA (not available) was indicated.
[a] MRI showed that experts had higher activity in inferior parietal lobule and inferior frontal gyrus than Novices during action anticipation.

Table 4
Search Results for Studies in Medicine-Related Domains

Study	Domain	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Observed differences in expert's gaze behavior	Expert's search strategy
Balslev et al. (2012)	Pediatric neurology	Experts: n = 12; Specialists (18.3y); Intermediates: n = 16; Residents (1.5y); Novices: n = 16; Students	Diagnosing videos of children with seizures or disorders imitating seizures	No group differences	Higher in experts	Longer fixation durations and larger number of fixations on relevant ROIs. No reports on other gaze characteristics.	*Selective attention allocation*
Bertram, Helle, Kaakinen, and Svedström (2013)	Radiology	Experts: n = 9 CT radiographers; Intermediates: n = 7 radiologists; Novices: n = 22 psychology students	Detection of enlarged lymph nodes (ELNs) and/or visceral abnormalities	NA	Higher in experts	Experts used shorter saccade amplitudes, fewer fixations and their fixation duration increased when ELNs were present. Experts fixated also more on the most relevant area compared to the two other groups.	*Slow and adaptive visual search rate*
Bertram et al. (2016)	Radiology	Experts: n = 12; specialists (2–22y); Intermediates: n = 14; Advanced residents (1.5–3.5y); Novices: n = 15; Early residents (<1.5y)	Lesion detection in abdominal CT scans	NA	Higher in experts	Overall, shorter fixation durations in specialists and advanced residents than in early residents. Longer fixation durations in specialists and advanced residents but not in early residents at high image presentation rate. Longer fixation durations and shorter saccade lengths in specialists at the presence of lesions in CT images.	*Faster and adaptive visual search rate and visual span*
Crowe, Gilchrist, and Kent (2018)	Neurology	Novices: n = 18; medical students: n = 10 (third year students: n = 8; fourth year students: n = 2); Experts: n = 7 (2.5y of experience: n 3; 8y: n = 2; 12y: n = 2)	MRI brain interpretation	NA	Experts were more accurate than medical students, who were more accurate than novices.	Scan match similarity scores indicate that experts displayed the most similar scanning patterns then medical students, followed by novices.	*Systematic search*
Donovan & Litchfield (2013)	Radiology	Experts: n = 10; consultant radiologists/ radiographers Intermediates: n = 10; third year undergraduate students Intermediates: n = 10; first year undergraduate students; Novices: n = 10; Naïve observers	Lung nodule detection in chest x-ray	No group differences	Lower in naïve observers	Shorter time to first hit nodules in experts than in the three other groups. However, group differences were not significant. Experts made fewer fixations at nodules than first years but not third years or naïve observers. Naïve observers made fewer fixations at nodules than first and third years. Experts made shorter dwells on nodules than first years and third years but not as compared to naïve observers.	*Visual span*

(*table continues*)

Table 4 (*continued*)

Study	Domain	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Observed differences in expert's gaze behavior	Expert's search strategy
Dreiseitl, Pivec, and Binder (2012)	Dermatology	Experts: $n = 3$; more than 5 years of training; Intermediates: $n = 4$; 2–5 years of training; Novices: $n = 9$; less than 2 years of training	Diagnosis of pigment skin lesion images	Faster in experts	No group difference	Overall, shorter fixation durations and fewer fixations in experts as compared to intermediates and novices. Experts made shorter saccades and performed a more systematic scanning of the image than intermediates and novices.	*Slower visual search rate & systematic search*
Gegenfurtner, Lehtinen, Jarodzka, and Säljö (2017)	PET/CT medical image diagnosis	Experts: $n = 9$ medical professionals from radiology and nuclear medicine departments; novices: $n = 14$ first-, second-, and third-year students of medicine (no prior knowledge in interpreting medical visualizations)	Interpreting PET/CT visualizations before and after exposure to eye movement modeling examples	Faster during baseline task	Higher in experts.	After instruction, experts fixated more on task-relevant areas compared to novices. Fixation duration on task-relevant areas in the baseline task was shorter than both retention and transfer tasks. Fixation duration on task-redundant areas was shorter in the retention task compared to transfer task	*Selective attention allocation*
Grundgeiger, Klöffel, Mohme, Wurmb, and Happel (2017)	Anesthesia	Experts: $n = 12$ senior anesthetists; Novices: $n = 12$ junior anesthetists	Monitoring and manual tasks in real and simulated anesthesia situations (scoring of accuracy based on question round)	NA	No group differences	Experts dwelled longer on the relevant area for that task	*Selective attention allocation*
Jaarsma, Jarodzka, Nap, van Merriënboer, and Boshuizen (2015)	Histopathology	Experts: $n = 13$; clinical pathologists, average 21y (±10) of training Intermediates: $n = 12$; Residents, average 3.0 y (±1.60) of training; Novices: $n = 13$; first year medical students	Diagnosis from microscopic images	Faster in experts.	NA	No differences in fixation durations or saccade amplitudes. Longer time-to-first-hit on diagnostically relevant area (DRA) and fewer visits of RDAs by experts than intermediates or novices.	*Visual span*
Krupinski (1996)	Mammography	3 staff mammographers (15; 10 and 8 years); 3 radiology residents (4; 3 and 3 years)	Lesion detection in mammographic images	NA	Higher in experts	False-negative decisions were associated with longer gaze durations than true-negatives. Readers with more experience tended to detect lesions earlier in the search than did readers with less experience, but those with less experience tended to spend more time overall searching the images and cover more image area than did those with more experience.	*Visual span (expertise) and faster visual search rate (performance)*
Krupinski, Chao, Hofmann-Wellenhof, Morrison, and Curiel-Lewandrowski (2014)	Dermatology	Experts: $n = 2$; Over 20 years of clinical experience as dermatologists Novices: $n = 2$; first year dermatology residents.	Diagnosis of pigment skin lesion images before and after inclusion in a training program.	NA	No group difference	No differences in viewing time from baseline to post-training. Dermatologists showed shorter dwells and made fewer fixations than residents.	*Slower visual search rate*

(*table continues*)

Table 4 (*continued*)

Study	Domain	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Observed differences in expert's gaze behavior	Expert's search strategy
Litchfield & Donovan (2016)	Radiology	Experts: $n = 14$; trained radiologists; > 10y of experience; Novices: $n = 14$; no experience.	Windowed search for everyday objects (Exp. 1) or lung nodules (Exp. 2).	No group differences.	Higher in experts (Exp. 2).	No group differences in gaze behavior characteristics (both Exp. 1 and Exp. 2).	*NA*
		Experts: $n = 19$; trained radiographers; > 3y of experience Novices: $n = 22$; no experience.	Windowed search for detection of abnormalities.	Shorter in experts.	Higher in experts.	No group differences in gaze behavior characteristics.	*NA*
Mallett et al. (2014)	Radiology	65 Experienced (27; >200 cases) and less experienced (n = 38; <199 cases) readers	Identification and pursuit of polyps on endoluminal 3D CT colonographic videos.	No group differences	No group difference	Time to first pursuit was significantly shorter in experienced readers. No differences regarding the remaining gaze characteristics (pursuit time and pursuit rate).	*Visual span*
Manning, Ethell, Donovan, and Crawford (2006)	Radiology	Experts: $n = 8$; experienced radiologists. Intermediates: $n = 5$; radiographers before and after 6 months training in chest image interpretation, Novice: $n = 8$ undergraduate radiography students	Lung nodule detection and identification in chest x-ray.	Shorter in experts	Higher in experts and intermediates.	Pre-trained radiographers and novices made more fixations than experienced radiologists. Number of fixations made by radiographers reduced significantly after training. Distance between fixations for the experienced radiologists was significantly larger than that for the other groups individually or combined. Radiologists made the fewest fixation visits per zones as compared to the other groups. Visual coverage reduced with increasing level of experience but this result did not reach significance	*Visual span and slower visual search rate*
Nodine, Kundel, Lauver, and Toto (1996)	Mammography	Experts: 3 mammographers (4–15 y) and 2 mammography technicians (2–7 y); Intermediates: 5 radiology residents (2–3 w); Novices: 5 laypersons with no experience	Searching mammogram pairs for breast masses	NA	Higher in experts	Experts had faster search times and a more efficient scanning pattern. Less-experienced mammographers dispersed their visual attention wider between potential breast masses and focused too much on breast parenchyma. They were also more distracted by bright blobs (high salience regions) that distracted the search by capturing visual attention.	*Faster visual search rate, visual span and selective attention allocation*

(*table continues*)

Table 4 (*continued*)

Study	Domain	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Observed differences in expert's gaze behavior	Expert's search strategy
Schulte-Mecklenbeck et al. (2017)	Psycho-diagnosticians	Novices: $n = 29$; Experienced psychodiagnosticians: $n = 21$ (11.1y experience ± 7.8y)	Diagnostic task: indicate which of two diagnostic labels best fit the case and accurately	No group differences	No group differences	No effect for expertise on total dwell time More time spend on diagnostic than non-diagnostic cues For correct response, a higher diagnostic gaze proportion resulted	*Difference observed for gaze proportion (only performance related).*
O'Neill, et al. (2011)	Ophthalmology	Experts: $n = 7$; Glaucoma subspecialists; Novices: $n = 23$; Ophthalmology trainees	Diagnosis for probability of glaucoma from examination of eye-disc photographs	Longer in trainees	NA	Participants who made the correct diagnosis for glaucoma likelihood spent a greater proportion of total time examining AOIs than those who made incorrect diagnosis irrespective of the training level. Experts adopt systematic gaze behavior when examining the optic nerve and retinal nerve fiber layer.	*Selective attention allocation and systematic viewing*
Wood et al. (2013)	Radiology	Experts: $n = 10$; post-fellowship senior registrars and consultants. Intermediates: $n = 10$; pre-fellowship radiology trainees. Novices: $n = 10$; undergraduate radiography students.	Report skeletal radiographs.	Shorter in experts compared to novices but not intermediates.	Higher in experts.	No group differences in search rate. Experts fixated on the area of fracture faster as compared to the novice and intermediates. Experts were quicker to fixate on the fractures on the subtle cases compared. No differences were evident between groups on the obvious cases. Experts spent more time fixating the fracture compared to novices but not intermediates. Group differences in duration of fixation between experts and intermediates were found only for inspection of subtle cases. Negative significant correlation between time to first fixation on fracture and diagnostic accuracy.	*Visual span and selective attention allocation*
Wood, Batt, Appelboam, Harris, and Wilson (2014)	Cardiology	Experts: $n = 10$; consultant emergency department physicians Novices: $n = 10$; medical students	ECG interpretation	Shorter in experts.	Higher in experts	Experts were significantly faster to dwell on the critical leads as compared with novices. No significant group difference in search rate.	*Visual span*

Note. Number of participants group (n) is indicated per each experience level according to the study (E = experts, I = intermediates, N = novices). The experience level is indicated as the average number of years (y), months (m), weeks (w) or hours of practice. If response time (RT) is measured, the outcome for more experienced compared to less experienced counterparts is indicated. This is either faster, slower or equal. If an accuracy outcome is measured, the outcome for more experienced compared to less experienced counterparts is indicated. This is either higher, lower or the same. If the essential measures were not reported, NA (not available) was indicated.

Table 5
Search Results for Studies in Other Domains

Study	Domain	Participants	Perceptual-cognitive task	Performance		Differences in gaze behavior as function of expertise	Expert's visual search strategy
				Response time	Accuracy		
Bauer and Schwan (2018)	Art	Experts: n = 21 students of art history; Novices: n = 25 other students	Think aloud inspection task + quiz at the end of the inspection of the paintings	No group difference	Experts were more accurate in answering the quiz questions	The average fixation duration was equal in experts and novices. Experts had a lower dwell time ratio, indicating that in relation to the dwell time on human features, experts' dwell time on symbols was higher than that of the novices.	*Selective attention allocation*
Bilalić et al. (2011)	Chess	Experts: n = 8 (≥2000 Elo points); Novices: n = 8 hobby players	Check task: indicate if the black chess piece was giving check to the white king (artificial 3 × 3 chess board)	Faster in experts	NA	Experts fixated less on chess pieces and more on the center of the board compared to novices.	*Visual span*
Dong, Zheng, Liu, and Meng (2018)	Geography	Experts: n = 16 geographers (followed the education for more than 2 years); Novices: n = 26 students with major in science	Determination task: Topographic maps were shown and questions had to be answered.	Faster in experts	Higher in experts	Experts had a higher fixation frequency (fixation per second), but a lower average fixation count and used fewer saccades. Geographers tended to focus on the marked area first, then glance at the nearby areas, searching for useful information to solve the problem.	*Slower visual search rate*
Dyer, Found, and Rogers (2008)	Forensic document examination (FDE)	Experts: n = 8 FDEs; Novices: n = 12	Discriminating between forged and disguised signatures	Slower in experts (50% longer)	Higher in experts	A very similar search strategy was employed by both groups, suggesting that visual inspection of signatures is mediated by a bottom up search strategy.	*NA*
Francuz, Zaniewski, Augustynowicz, Kopiś, and Jankowski (2018)	Art	Experts: n = 23 students of art history; Novices: n = 19 students in social sciences and humanities	Recognition of balanced compositions	NA	Higher in experts	Eye movements of people who more accurately appreciated paintings with balanced composition showed shorter dwell time, shorter first and shorter average fixation duration and lower number of fixations (only in expert group). The number of fixations on unknown paintings was much higher than on known ones but only in experts.	*Slower visual search rate (related to performance) and adaptive visual search rate (related to expertise)*

(*table continues*)

Table 5 (*continued*)

Study	Domain	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Godwin et al. (2015)	Military	Experts: n = 21 experienced; Novices: n = 21 inexperienced (all military personnel)	Decision-making task: evaluation of potential risk indicators (PRI) (halt-patrol or continue-patrol)	Faster in experts	NA	Longer fixation durations prior to a halt-patrol response than a continue-patrol response in both groups. Experts used fewer fixations compared to novices. More fixations were made prior to continue-patrol responses in both groups. Saccade amplitudes were greater prior to halt-patrol than continue-patrol responses in both groups. Both participant groups spent a similar proportion of the trial time inspecting the PRIs as they evaluated threat. Experts visited PRI's more often than novices.	*Adaptive visual search (related to scene) and slower visual search rate in experts*
Hosking, Liu, and Bayly (2010)	Motorcycle riding	Experienced in both motorcycle riding and car driving (EM-ED): n = 14; Inexperienced motorcycle riders and experienced drivers (IM-ED): n = 14; Inexperienced in both motorcycling riding and car driving (IM-ID): n = 9	Hazard detection task using a motorcycle simulator	Faster in EM-ED > IM-ED > IM-ID	NA	Compared to the IM-ID group, both the EM-ED and IM-ED groups exhibited more flexible visual scanning patterns that were sensitive to the presence of hazards: Longer fixations on hazards in rural scenarios than in residential scenarios in both groups. All participants fixated on the hazards at approximately the same time, but EM-EDs responded faster. Fixation variations were larger in the horizontal plane than in the vertical plane, the spread of fixations were significantly different for the IM-ED group in the no hazard condition compared to the IM-ID group in the hazard condition. In hazard conditions, fewer deviations from the center of the visual field were made compared to the no hazard conditions in the EM-ED and IM-ED groups.	*Adaptive visual span*

(*table continues*)

Table 5 (*continued*)

Study	Domain	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Huestegge, Skottke, Anders, Müsseler, and Debus (2010)	Driving	Experienced drivers: n = 20; Inexperienced drivers: n = 20	Hazard detection task braking response or speed reduction by pushing space button on keyboard (pictures)	Faster in experts	NA	Time to first fixation, mean number of fixations and average fixation duration per scene did not differ between both groups. More fixations used in scenes with high braking affordance compared to medium braking affordance. Expert drivers tend to scan with shorter saccade amplitudes (not significant).	*NA*
Lansdale, Underwood, and Davies (2010)	Aerial photography	Experienced analysts of aerial photographs (14.4y): n = 7; Untrained students: n = 7	Change detection and memory task	NA	Higher in experts (in both tasks)	Untrained viewers fixated preferentially upon salient features throughout stimulus presentation whereas experts did not. Experts diverge in where they look after an initial consistency but untrained viewers remain consistent between themselves in their fixation locations over the entire presentation of the stimulus	*Selective attention allocation*
MacKenzie and Westwood (2015)	Occupational therapy	Experts: n = 10; Novices: n = 10	Safety rating task (safety ratings for stroke-related image content)	NA	Higher in experts	The number and duration of fixations and number and amplitude of saccades did not differ between both groups. There was also no difference between groups in the fixation count and duration on important AOIs	*NA*

(*table continues*)

Table 5 (*continued*)

Study	Domain	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Marzouki, Dusaucy, Chanceaux, and Mathôt (2017)	Gaming	Experts: $n = 4$; Novices: $n = 4$	Off-game questionnaire testing knowledge and acquired skills through completed raids in the game	NA	Higher in experts	Correlation between pupil size and tendency to look at salient locations (measure for mental effort). This correlation was stronger in experts. Experts improve control over their eye-movement behavior by guiding their eyes towards informative, but potentially low-salient areas of the screen. The fixation distribution analysis shows that experts focused more on particular areas than novices and oppositely attributed importance to some spatial regions on the screen. Novices fixate more on the central zone; whereas experts divide their attention over the central zone and other meaningful areas.	*Selective attention allocation and visual span*
Page, Bates, Long, Dawes, and Tipton (2011)	Lifeguard surveillance	Experts: $n = 56$ lifeguards (8.4 y); Novices: $n = 13$ lifeguards with < 1 season experience	Detection of drowning individuals from animated movie	NA	Higher in experts	No significant differences between the visual search patterns of the groups. Experts fixated more on the middle compared to the back row Biased condition). All lifeguards fixated more on the middle compared to the front row. There was no difference in number of fixations per minute between both groups. Experts used a longer fixation duration compared to novices (non-biased condition), but this was not the case in the biased condition. No difference in number of fixations between accurate and non-accurate performers.	*NA*

(*table continues*)

Table 5 (*continued*)

Study	Domain	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Prytz, Norén, and Jonson (2018)	Emergency responders	Experts: $n = 17$ (rescue and ambulance service personnel); Novices: $n = 20$	Decision task: analysis of accident and control images	Shorter in novices	Higher in experts	No group effects for dwell time, mean fixation duration or number of fixations. Experts fixated longer on task relevant areas compared to novices. Shortest dwell times for traffic-accident-without-injury category. Novices had shorter dwell times and sorter mean fixation durations than the experts. The rescue service personnel also had shorter mean fixation duration than the ambulance personnel for the traffic-accident-without-injured category. The smallest fixation count was observed for the traffic-accident-without injury category.	*Selective attention allocation and slower and adaptive visual search rate*
Reingold, Charness, Pomplun, and Stampe (2001)	Chess	Experts: $n = 8$ (CFC: $M = 2278$); Intermediates: $n = 8$ (CFC: $M = 1483$); Novices: $n = 16$ inexperienced chess players	Change blindness flicker paradigm: reconstruct chess positions (20 chess pieces) and a check detection task on a 3×3 chessboard.	Task 1 and 2: Faster in experts	Task 2: Higher in experts	Task 1: Experts used larger saccade amplitudes. Task 2: Experts made fewer fixations per trail that less skilled players and fixated more to the center of the board than on the chess pieces. There was no difference in average fixation duration between the groups. In trials in which eye-movements occurred, experts used shorter saccades; fewer fixations on average and fewer fixations on chess pieces.	*Slower visual search rate and visual span*
Schriver, Morrow, Wickens, and Talleur (2008)	Aviation	Experts: $n = 14$ pilots (mean total flight hours: 481.9 ± 317.2); non-experts: $n = 14$ pilots (mean total flight hours: 110.5 ± 62)	Decision making simulated flight task with failing flights	Faster when cues were high versus low in diagnosticity in both groups and faster in experts when cues were correlated	Higher in experts	Higher percentage of dwell time on AOIs when a failure was present, this was more pronounced in experts. Attention to cues was associated with decision accuracy.	*Selective and adaptive attention allocation*

(*table continues*)

Table 5 (*continued*)

Study	Domain	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Sheridan and Reingold (2014)	Chess	Experts: $n = 17$ (CFC: $M = 2223$); Novices: $n = 24$ (unrated club players)	Decision-making task: select white's best move	Faster in experts (not significant)	Higher in experts	Longer dwell time on relevant AOIs in both groups. Novices used longer dwells than experts. Experts dwelled faster in fixating the relevant AOI. Increased number of fixations for relevant compared to irrelevant AOIs in experts. Mean fixation duration of first dwell did not differ between groups. Experts showed stronger and earlier relevancy effects than the novices (of the first five fixations more were in relevant AOIs in experts compared to novices).	*Selective attention allocation and visual span*
Topczewski, Topczewski, Tang, Kendhammer, and Pienta (2017)	Organic chemistry	Experts: $n = 12$ graduate and advanced graduate students; Novices: $n = 15$ second-semester organic chemistry students	Examination of proton NMR spectra	NA	Higher in experts	Experts focused on the spectrum for their first three fixations and on the correct answer for the last three fixations, whereas novices fixated more on the distractors and the white space for their first and last three fixations. The expert group fixated longer during the last three fixations than did the novice group. The duration pattern of the advanced novices was similar to that of the experts except for the second fixation, whereas the duration patterns for the early novices were different from those of the other two groups of participants. (novices were split into two groups based on their performance)	*Selective attention allocation and slower visual search rate*

(*table continues*)

Table 5 (*continued*)

Study	Domain	Participants	Perceptual-cognitive task	Performance: Response time	Performance: Accuracy	Differences in gaze behavior as function of expertise	Expert's visual search strategy
Van Meeuwen et al. (2014)	Air traffic controlling (ATC)	Experts: $n = 10$ fully licensed ATCs ($M = 7.10 \pm 6.83$y); Intermediates: $n = 9$ students in the final phase of ATC training program ($M = 22.33 \pm 6.20$m); Novices: $n = 12$ students in the initial phase of the ATC training program ($M = 3.25 \pm .45$m)	Decision-making task: provide the optimal order of arrival of all depicted aircrafts (radar screen pictures)	Faster in experts compared to the two other groups	Higher in experts and intermediates compared to novices	The dwell time was shorter and number of fixations was lower on the aircraft, longer on the Artip and the background area, fewer transitions between different aircrafts and between background and aircraft and a shorter time to first fixate the Artip was observed in easy tasks. Experts fixated less on the background area and used fewer transitions between the background and the aircraft than the two other groups in easy tasks and intermediates fixated more on the background in difficult tasks compared to the other groups. In difficult tasks, a longer time to first fixate the aircraft was used. This was shorter in experts in medium and difficult tasks. Dwell time did not differ between groups. Novices dwelled longer on the Artip, used more fixations on the Artip and took more time to first fixate on the aircraft, but less time to first fixate on the Artip. Intermediates dwelled longer on the background area than experts. And experts used fewer transitions between Artip-aircraft, Artip-background and background-aircraft.	*Selective and adaptive attention allocation and visual span*

Note. Number of participants per group (*n*) is indicated per each experience level according to the study. The experience level is indicated as the average number of years (y), months (m), weeks (w), hours of practice, or domain-specific measures (e.g., elo of CFC = Canadian Chess Federation). If response time is measured, the outcome for more experienced compared with less experienced counterparts is indicated. This is either faster-lower or the same. If an accuracy outcome is measured, the outcome for more experienced compared with less experienced counterparts is indicated. This is either higher or lower or the same. If the essential measures were not reported, NA (not available) was indicated.

Table 6
Overview of Tasks, Performance, and Eye-Movement Characteristics in Sports

Task	Study/Expertise domain	Acc.	RT/DT	Fix dura.	Total # of fix.	# of loc. Fix.	Fix dur. on AOI	# of fix on AOI	Dwell time in AOI	# of dwells to AOI	Time to first fix on AOI	Sacc amp.	Time to first dwell	Syst. scan pattern
OPT-MAX/Anticipation	Mori & Shimada (2013)/ Rugby	=	↓ 1.85				↑ .97							
OPT-MAX/Anticipation	North et al. (2009)/Soccer	↑ 1.85	=	.00	.77	↑ 1.22	.35							
OPT-MAX/Anticipation	Piras et al. (2014)/ Volleyball	↑ .87	↓ .84	↓ 1.88	↓ 2.98									
OPT-MAX/Anticipation	Savelsbergh et al. (2002)/ Soccer	↑ 1.28[a]; ↑ 1.31[a]		↑ 1.92[a]	↓ 3.06[a]	↓ 1.37[a]	↑ .91[a]							
OPT-MAX/Anticipation	Vansteenkiste et al. (2014)/ Volleyball	↑	↓		↑	↑		↑						
OPT-MAX/Anticipation	Williams et al. (1994)/ Soccer	↑ 2.70[a]	↓ 1.88[a]	↓ 1.50[a]	↑ 1.62[a]		↑ 2.16[a]							
OPT-MAX/Anticipation	Williams & Davids (1998)/ Soccer	↑ 2.21[ad]; ↑ 2.08[ae]	↓ 1.20[abd] ↓ .94[ae]	.77[ad]; ↓ .85[e]	.19[ad]; ↑ .91[e]		.13[ao]; ↑ 1.08[ae]							.04[ad]; ↑ .83[ae]
OPT-MAX/Anticipation	Williams et al. (2002)/ Tennis	.49	↓ 1.77	.20	.17	.59		↑ 1.22[a]						↑ .56
OPT-MAX/Decision	Lex et al. (2015)/Soccer		↓ 1.09	.00	↓ 1.06	↓ 2.00								
OPT-MAX/Decision	Ryu et al. (2015)/ Basketball	↑ 2.85	↓ 1.03	↑ .94			↑ .67					↓ .67		
OPT-MAX/Decision	Vaeyens et al. (2007)/ Soccer	↑ 2.00	↓ .70[b]	.35	↑ 1.00		↑ 1.85[b]							↑ .87
OPT-MAX/Detection	Laurent et al. (2006)/ Basketball	↑ 2.30; ↑ 1.81		.14	↑ ↓ 1.31									
MAX/Anticipation	Crespi et al. (2012)/ Billiard	↑ 1.53[a]	↓ 1.37[a]	=			=	↑				=		↑
MAX/Anticipation	Núñez et al. (2009)/Soccer	.00[a]	↓ .74[a]				↑ 1.01[a]							
MAX/Anticipation	Piras et al. (2017)/Table tennis	↑ .51	↓ .52	↑ .65	↓ .43		↑ .51	↑ .35				.03		
MAX/Decision	Hancock & Ste-Marie (2013)/ Ice-Hockey	↑ .80		.30	.01									
MAX/Detection	Canal-Bruland et al. (2011)/ Soccer		.67	↑ .70	↓ .84							.29		
OPT/Decision	Milazzo et al. (2016)/Karate	↑ 2.55	↓ 2.30	↑ 1.92	↓ 4.13	↓ 5.67[a]	↑ 1.88							
OPT/Decision	Ripoll et al. (1995)/Boxing	↑ 3.36[ab]	=		↓		↑	↑						↑
OPT/Detection	Gorman et al. (2015)/ Basketball	↑ 2.17[b]		=			↑							
Nonexplicit/Anticipation	Alder et al. (2014)/ Badminton	↑ .86		↑ 1.33[a]	.27[a]			↑ 2.21						
Nonexplicit/Anticipation	Casanova et al. (2013)/ Soccer	↑ 2.30		.70	.70	.70		.84						
Nonexplicit/Anticipation	Hagemann et al. (2010)/ Fencing	↑ .94		.29[a]	.29[a]		↑ 1.03							
Nonexplicit/Anticipation	Manzanares et al. (2017)/ Sailing	↑ .79[a]		↓ .39	↑ .85		↑ 1.10[b]	↑ 1.24[b]						
Nonexplicit/Anticipation	McRobert et al. (2009)/ Cricket	↑ 4.76		.55	.51	↑ 1.22	↑ .87							
Nonexplicit/Anticipation	Roca et al. (2013)/Soccer	↑ 4.76		↓ 2.73	↑ 3.77	↑ 3.66	↑ 2.26							
Nonexplicit/Anticipation	Uchida et al. (2014)/ Basketball	↑ 1.62					↑ .87							

(*table continues*)

Table 6 (*continued*)

Task	Study/Expertise domain	Acc.	RT/DT	Fix dura.	Total # of fix.	# of loc. Fix.	Fix dur. on AOI	# of fix on AOI	Dwell time in AOI	# of dwells to AOI	Time to first fix on AOI	Sacc amp.	Time to first dwell	Syst. scan pattern
Nonexplicit/Anticipation	Wu et al. (2013)[*]/ Basketball	↑ 1.06[a]		.46[a]		↓ .27[a]		↓			↓			↑
Nonexplicit/Decision	Flessas et al. (2015)/ Rhythmic gymnastics	.00[a]							↑ 1.00[a]					
Nonexplicit/Decision	Pizzera et al. (2018)/ Gymnastics	↑ 7.98		=			↑ 1.67[c]	↑ 2.04[b]; ↑ 1.57[bc]						
Nonexplicit/Decision	Spitz et al. (2016)/Soccer	↑ 1.09		.06	.14			↑ .84						
Nonexplicit/Decision	Takeuchi & Inomata (2009)/ Baseball	↑ 2.00[a]	↓ 2.28[a]		↑ 1.81[a]	↑ 1.81[a]		↑						
Nonexplicit/Decision	Del Campo et al. (2018)/ Soccer	↑					↑ .50[a]	↑ .33[a]						
Nonexplicit/Decision	Schnyder et al. (2014)/ Soccer	↑ .35[a]		↑ 2.14[a]	↓ 1.35			.02[a]						
Nonexplicit/Detection	Campbell et al. (2014)/ Golf	↑ .49[a]		↑ 1.19[a]	↓ 1.06[a]		↓ .46[a]							
Nonexplicit/Detection	Gorman et al. (2013)/ Basketball	↑ 1.50					.73[b]							

Note. Accuracy (Acc.), reaction time (RT), detection time (DT), averaged fixation duration over the whole trial irrespective of location (Fix dura.), averaged total number of fixations over the whole trial irrespective of location (total # of fix.), number of locations fixated (# of loc. Fix.), fixation duration on area of interest (Fix dur. on AOI), number of fixations on area of interest (# of fix on AOI), number of dwells to AOI (# of dwells to AOI), saccade amplitude (Sacc amp.), systematic scan pattern (Syst. Scan pattern), in experts (E) and novices (N). Indicated values are Cohen's d' effect sizes. Values marked in grey resemble a significant effect for expertise. The arrows indicate whether this measure was higher (↑), lower (↓), or equal (=) in experts compared with the less-experienced group(s). In case the essential statistics to determine effect size Cohen's d' values were not provided in the paper only higher (↑), lower (↓), or equal (=) and not a value is shown describing differences in gaze between experts and less-experienced group(s).
[a] Effect sizes calculated based on the statistics indicated in the paper. [b] Averaged effect sizes. In the study of Pizzera et al. (2018) effect sizes were provided for both the difference between high- and low-level judges as well as between motor and no motor experience (indicated with [c] = difference between motor and no motor experience). In the study of Williams & Davids (1998) effect sizes were provided for two different tasks ([d] = all the values for the 3×3 task and [e] = all the values for the 1×1 task).

Table 7
Overview Domain, Performance, and Eye-Movement Characteristics in Medicine

Expertise domain	Study	Acc.	RT/DT	Fix dura.	Total # of fix.	# of loc. fix.	Fix dur. on AOI	# of fix on AOI	Dwell time in AOI	# of dwells to AOI	Time to first fix on AOI	Sacc. Amp.	Time to first dwell	Syst. scan pattern
Cardiology	Wood et al. (2014)	↑ 2.30	↓ 2.00		.00[a]								↓ 1.03	
Dermatology	Dreiseitl et al. (2012)	.67[a]	↓ 1.70[a]	↓ 2.67[a]	↓ 2.26[a]							↓ .97		↑
Dermatology	Krupinski et al. (2014)	5.06[a]		↓ .55[ac]	↓ .68[a]				↓ .56[ac]					
Histopathology	Jaarsma et al. (2015)		↓ .68[c]; ↓ .45[bc]	.63[a]					.29[a]	↓ .94*	↑ 1.06*	.29*		
Neurology	Balslev et al. (2012)	↑ 3.20[a]	.00[a]						↑ 2.08[a]					
Neurology	Crowe et al. (2018)	↑ 1.96												↑ 2.61[c]
Ophthalmology	O'Neill et al. (2011)		↓				↑		↓					↑
Radiology	Bertram et al. (2013)	↑ 1.31		=				↑ 1.28[a]				↓		
Radiology	Bertram et al. (2016)	↑ .22		↑ ↓ .79[a]								↓ .47*		
Radiology	Donovan & Litchfield (2013)	↑ 1.74[a]	.46[a]					↓ 1.34[a]	↓ 1.40[a]		↓ .81*			
Radiology	Litchfield & Donovan (2016)	.00	.00		.00						.00	.35		
Radiology	Mallett et al. (2014)	↑ .41	.09										↓ .11	
Radiology	Manning et al. (2006)	↑				↓		↓ 2.17[a]				↑		
Radiology	Wood et al. (2013)	↑	↓ 1.14[a]; ↓ .86[ab]		=	=	↑ .74[a]; ↑ .54[ab]				↓			
Mammography	Krupinski (1996)	↑ .68[a]							↓		↓			↑
Mammography	Nodine et al. (1996)	↑		↓			↑							
PET/CT	Gegenfurtner et al. (2017)	↑ 9.80	↓ .35[a]				↑ .07[a]	↑ .18[a]						
Clinical psychology	Schulte-Mecklenbeck et al. (2017)	=	=						=					
Anesthesia	Grundgeiger et al. (2017)	=							↑					

Note. Accuracy (Acc.), reaction time (RT), detection time (DT), averaged fixation duration over the whole trial irrespective of location (Fix dura.), averaged total number of fixations over the whole trial irrespective of location (total # of fix.), number of locations fixated (# of loc. Fix.), fixation duration on area of interest (Fix dur. on AOI), number of fixations on area of interest (# of fix on AOI), number of dwells to AOI (# of dwells to AOI), saccade amplitude (Sacc amp.), systematic scan patterns (Syst. Scan pattern), in experts (E) and novices (N). Values indicate effect size Cohen's d' values. Values marked in grey are statistical significant expertise effects. The arrows indicate whether this measure was higher (↑), lower (↓) or equal (=) in experts compared with the less-experienced groups. In case the essential statistics to determine effect size Cohen's d' values were not provided in the paper only higher (↑), lower (↓), or equal (=) and not a value is shown describing differences in gaze between experts and less-experienced group(s).
[a] Effect sizes calculated based on the provided statistics in the paper. [b] Effect sizes for the difference between experts and intermediates, in cases where three groups were compared. [c] Averaged effect sizes in cases were different conditions or AOIs were compared.

Table 8

Overview of Tasks, Performance, and Eye-Movement Characteristics in Other Domains of Expertise

Task	Study/Expertise domain	Acc.	RT/DT	Fix dura.	Total # of fix.	# of loc. fix.	Fix dur. on AOI	# of fix on AOI	Dwell time in AOI	# of dwells to AOI	Time to first fix on AOI	Sacc amp.	Time to first dwell	Syst. scan pattern
Nonexplicit/Inspection	Bauer and Schwan (2018)/Art	↑ 6.00[a]	=	=					↑ .84					
Nonexplicit/Decision	Bilalić et al. (2011)/Chess		↓ .30[a]					↓ .45[a]						
Nonexplicit/Decision	Francuz et al. (2018)/Art	↑ .80[a]		=	↓			=						
Nonexplicit/Decision	Godwin et al. (2015)/Military		↓ .87[a]	=	↓ .91[a]		=			↑ .77		=		
Nonexplicit/Decision	MacKenzie and Westwood (2015)/ Occupational therapy	↑ 2.45		=	1.15		=	=				1.06		
Nonexplicit/Decision	Marzouki et al. (2017)/Gaminig	↑ 3.10					↑							
Nonexplicit/Decision	Schriver et al. (2008)/Aviation	↑ 2.08[a]	↓ 1.28[a]						↑ 1.28					
Nonexplicit/Detection	Lansdale et al. (2010)/Aerial photography	↑ .33[d]; .63[d]						↑ 1.07[a]						
Nonexplicit/Detection	Page et al. (2011)/Lifeguards	↑		.35[b]	.29[b]		↑ .20[b]							
Nonexplicit/Detection	Reingold et al. (2001)/Chess	↑ .15[a]	↓ .32[a]	=	↓ .32[a]			↓ .24[a]				↑ .21[*]		
Nonexplicit/Detection	Hosking et al. (2010)/Motor riding		↓ 1.00			=	↑				=	↓ 1.15		
Nonexplicit/Determination	Dong et al. (2018)/Geography	↑ 1.00[a]	↓ .79[a]		↓ .19[ab]						↓			
Optimizing/Decision	Dyer et al. (2008)/FDE	↑ 1.13[a]	↑ .84					=						
Optimizing/Decision	Topczewski et al. (2017)/ Organic chemistry	↑					↑	↑						↑
Maximizing/Decision	Van Meeuwen et al. (2014)/ATC	↑ 1.96	↓ 1.85				↓ .59[c]; ↓ 1.60[c]	↓ 1.28[b]			↓ 1.53[b]			↑ .94[b]
Maximizing/Detection	Huestegge et al. (2010)/Driving		↓ .35[ab]	=	=						.41[ab]	↓ .59[*]		
Optimizing-Maximizing/Decision	Prytz et al. (2018)/Emergency responders	↑ .88[ab]	↑ 1.15	↑ .84	=				↑ 1.57					
Optimizing-Maximizing/Decision	Sheridan and Reingold (2014)/Chess	↑ 2.26[a]	↓ .56[a]					↑					↑	

Note. Accuracy (Acc.), reaction time (RT), detection time (DT), averaged fixation duration over the whole trial irrespective of location (Fix dura.), averaged total number of fixations over the whole trial irrespective of location (total #of fix.), number of locations fixated (#of loc. Fix.), fixation duration on area of interest (Fix dur. On AOI), number of fixations on area of interest (#of fix on AOI), number of dwells to AOI (#of dwells to AOI), saccade amplitude (Sacc amp.), systematic scan patterns (Syst. Scan pattern), in experts (E) and novices (N). Indicated values are effect size Cohen's d' values. Values marked in grey indicate statistically significant expertise effects. The arrows indicate whether this measure was higher (↑), lower (↓) or equal (=) in experts compared to the less-experienced groups. These signs are used in case the essential statistics to determine effect size Cohen's d' values were not provided in the paper. ATC = Air traffic controlling; FDE = Forensic document examination.

[a] Effect sizes calculated based on the statistics indicated in the paper. [b] Averaged effect sizes. In the study of van Meeuwen et al. (2014) effect sizes were provided for different AOIs (indicated with [c]). In the study of Lansdale et al. (2010), scores for different tasks were calculated, this result in two effect size values for accuracy (indicated with a [d]).

in sports included decision-making (e.g., Flessas et al., 2015) or detection (e.g., Campbell et al., 2014). A total of 12 of the studies were classified as optimizing-maximizing tasks, five as maximizing tasks, three as optimizing tasks, and 15 as nonexplicit tasks (see Table 6).

Medicine. In medicine, all perceptual-cognitive tasks involved detection of pathology or abnormality from XR-scans (e.g., Donovan & Litchfield, 2013), CT-scans (e.g., Bertram et al., 2016), PET/CT-scans (Gegenfurtner, Lehtinen, Jarodzka, & Säljö, 2017), lesion images (e.g., Dreiseitl, Pivec, & Binder, 2012), video clips (e.g., Balslev et al., 2012), MRI scans (Crowe, Gilchrist, & Kent, 2018), electrocardiogram (Wood, Batt, Appelboam, Harris, & Wilson, 2014), or monitoring during an anesthesia procedure (Grundgeiger, Klöffel, Mohme, Wurmb, & Happel, 2017). In all studies that included a detection task, except two (Schulte-Mecklenbeck, Spaanjaars, & Witteman, 2017; Wood et al., 2013), participants were either instructed to provide a report of their diagnosis or indicate with a mouse click the location of a possible pathology or abnormality, but no explicit instructions were given on the accuracy or speed of execution. Therefore, tasks in all these studies were classified as nonexplicit tasks. Only in two studies did participants receive specific instructions concerning speed and accuracy; these tasks were categorized as maximizing-optimizing tasks (Schulte-Mecklenbeck et al., 2017; Wood et al., 2013).

Other domains. In other domains of expertise, a wide variety of tasks were used. Some examples are (a) a hazard detection task while driving in traffic, (b) a chess detection task in which participants had to decide whether the position of a chess piece resulted in check, (c) a knowledge quiz at the end of analyzing a specific scene in a game or in art, and (d) decision-making in other domains (e.g., forensics, military, air traffic controlling). Based on task instructions, two studies used optimizing tasks, two used maximizing tasks, two used maximizing-optimizing tasks and in the other 12 studies nonexplicit task instructions were provided (see Table 8).

Performance and Gaze Features in Experts

In the following paragraphs, differences in performance and gaze characteristics between different level of expertise have been examined considering both the domain and type of the perceptual-cognitive task within the domain. Effect sizes and weighted mean effect sizes are presented in forest plots separately for each domain of expertise (Figures 2–4 for sports, Figure 5 for medicine, and Figure 6 for other domains). For several gaze features in sports, namely those for which sufficient studies effect size measures or descriptive statistics reported (≥10 studies; e.g., average fixation duration, average number of fixations and fixation duration on AOI) publication bias analyses are conducted and presented in funnel plots (Figure 2D through 2F and Figure 3C). These measures are discussed in detail below.

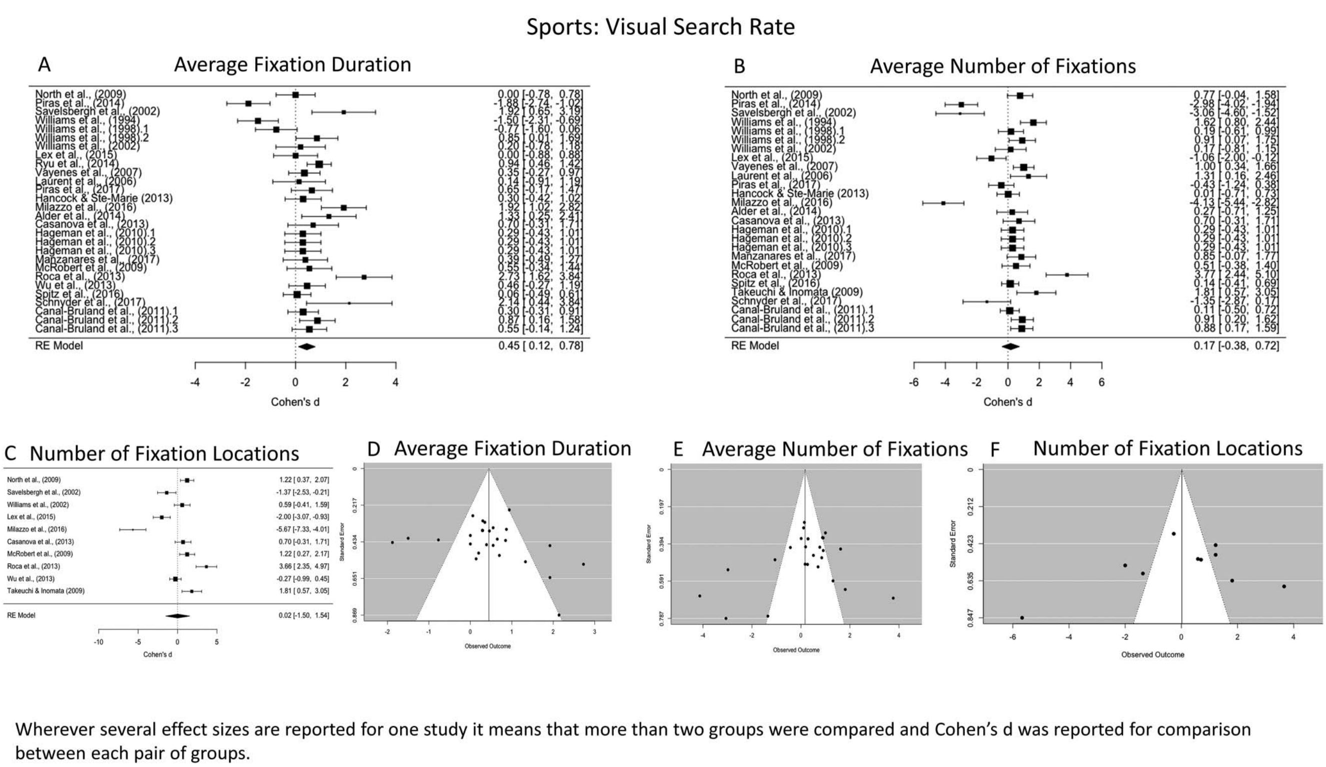

Figure 2. Eye-movement char acteristics of visual search rate in sports. Forest plots and funnel plots, respectively. (A and D) Average fixation duration. (B and E) Average number of fixations. (C and F) Number of fixation locations.

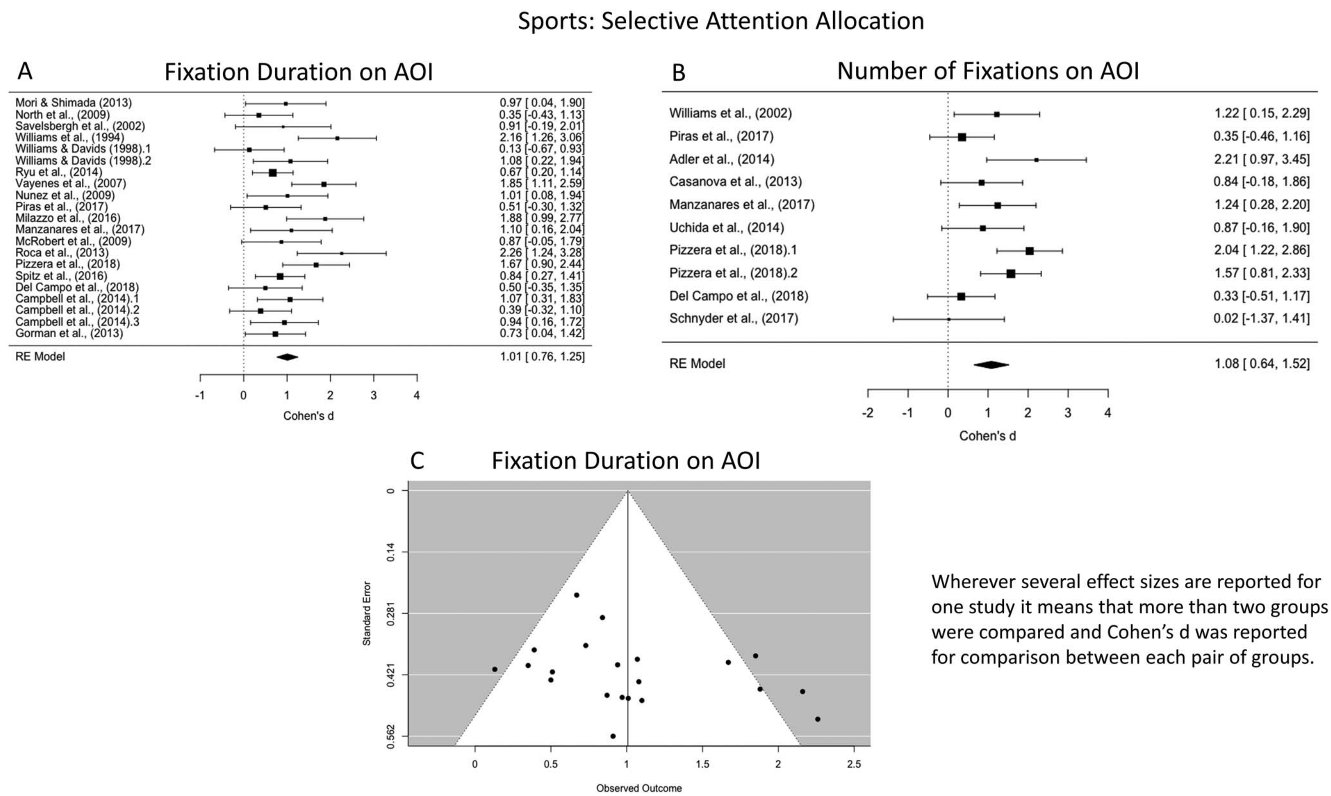

Figure 3. Eye-movement characteristics of selective attention allocation in sports. Forest plots and funnel plot, respectively. (A and C) Fixation duration on AOI. (B) Number of fixations on AOI.

Expert Performance and Gaze Features in Sports

Performance. Observations from the 36 studies involving sports suggest that irrespective of the task, experts were more accurate and/or made faster responses than their nonexpert counterparts. Superior performance on both speed and accuracy was found in nine of the 17 studies for which both measures were available (see Table 3).

Gaze features. Figures 2–4 present forest plots and weighted average effect sizes for all eye-movement characteristics in sports. In general, moderate to large weighted mean effect sizes were found for the average fixation duration, fixation duration on AOI, number of fixations on AOI, and systematic scan pattern.

Significant differences between experts and novices or intermediates in one or more gaze features were reported in all but four studies (see Table 3). In three of those studies, a higher accuracy was reported in experts (Casanova et al., 2013; Gorman, Abernethy, & Farrow, 2013; Hancock & Ste-Marie, 2013) and in one study, a faster response time was reported in experts (Núñez et al., 2009). The lack of a difference in gaze behavior between experts and nonexperts may have been attributable to the experts' ability to encode domain-specific information that is relevant to the task more efficiently (Page et al., 2011) or attributable to insufficient statistical power (sample sizes were $N = 16$ and $N = 20$ in Casanova et al., 2013 and Núñez et al., 2009, respectively). The effect size analyses mostly report moderate to large effects for the reported eye-tracking measures in all but one of those studies (Hancock & Ste-Marie, 2013; Figures 2 and 3). Moderate and large effect sizes should not be disregarded as they may imply practical significance, even with statistically nonsignificant results (Ellis, 2010). Expertise-related changes in gaze features are discussed in more detail in the following paragraphs (see Table 6).

Visual Search Rate

The eye-movement characteristics that were associated with visual search rate (i.e., average number of fixations, number of fixation locations over the whole scene, or combinations of these two measures) were examined in 26 of the 36 studies included. In 19 studies, differences between expertise groups in one or more of the eye-movement characteristics were observed. In 10 of these studies, visual search rate in experts was faster than that observed in novices or intermediates (i.e., more fixations or fixations on more locations), whereas in the remaining studies visual search rate in experts was slower than that observed in nonexperts (i.e., fewer fixations or fixations on fewer locations). The findings reported in the remaining seven studies showed no differences in visual search rates between experts and nonexperts.

A slower visual search rate was most often observed in combination with longer fixation durations in experts compared with nonexperts (see Table 6). An analysis of the effect sizes of the studies reporting differences in visual search rate between experts and nonexperts indicated that all measures for assessing the visual search rate (i.e., number of fixations, number of fixated areas, and fixation duration) are highly relevant predictors for expertise (Figure 2A through 2C). In addition, although the effect sizes were

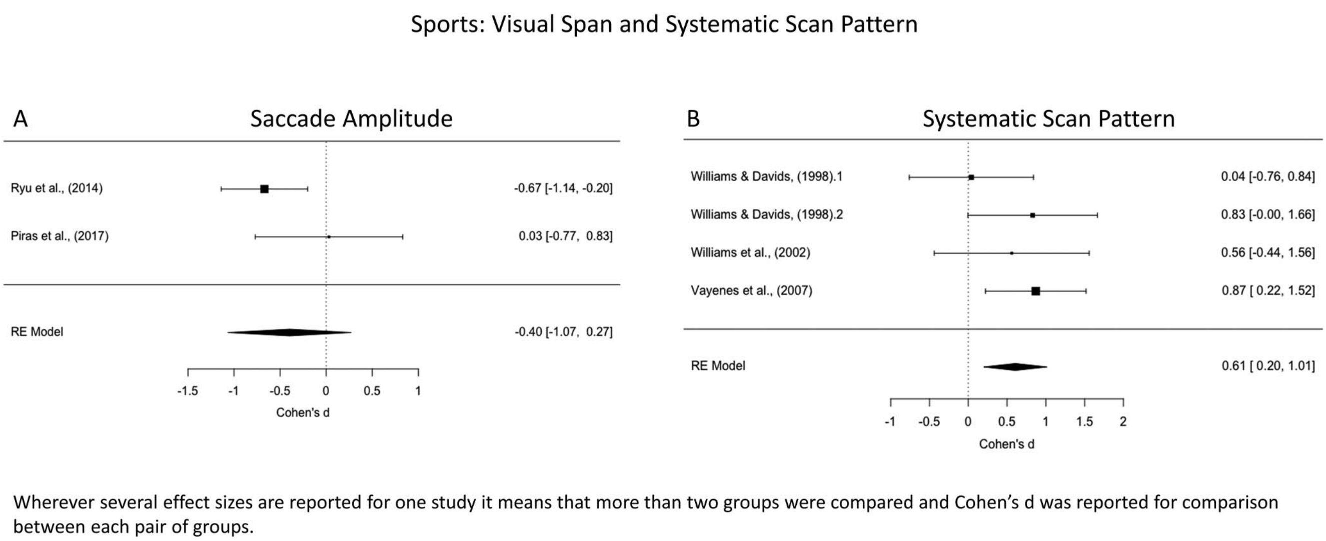

Figure 4. Eye-movement characteristics of visual span and systematic scan pattern in sports: (A) Saccade amplitude. (B) Systematic scan pattern.

generally small for visual search rate in most studies that failed to show statistically significant differences between expertise groups, Schnyder et al. (2014) reported a large effect for number of fixations and Casanova et al. (2013) reported a moderate effect for the number of fixations and the number of fixation locations. Furthermore, five studies indicated that visual search rate can be influenced by the task settings (see Table 3). For example, Roca, Ford, McRobert, and Williams (2013) showed that the eye-movement characteristics of experience soccer players varied between far and near play situations during performance of an

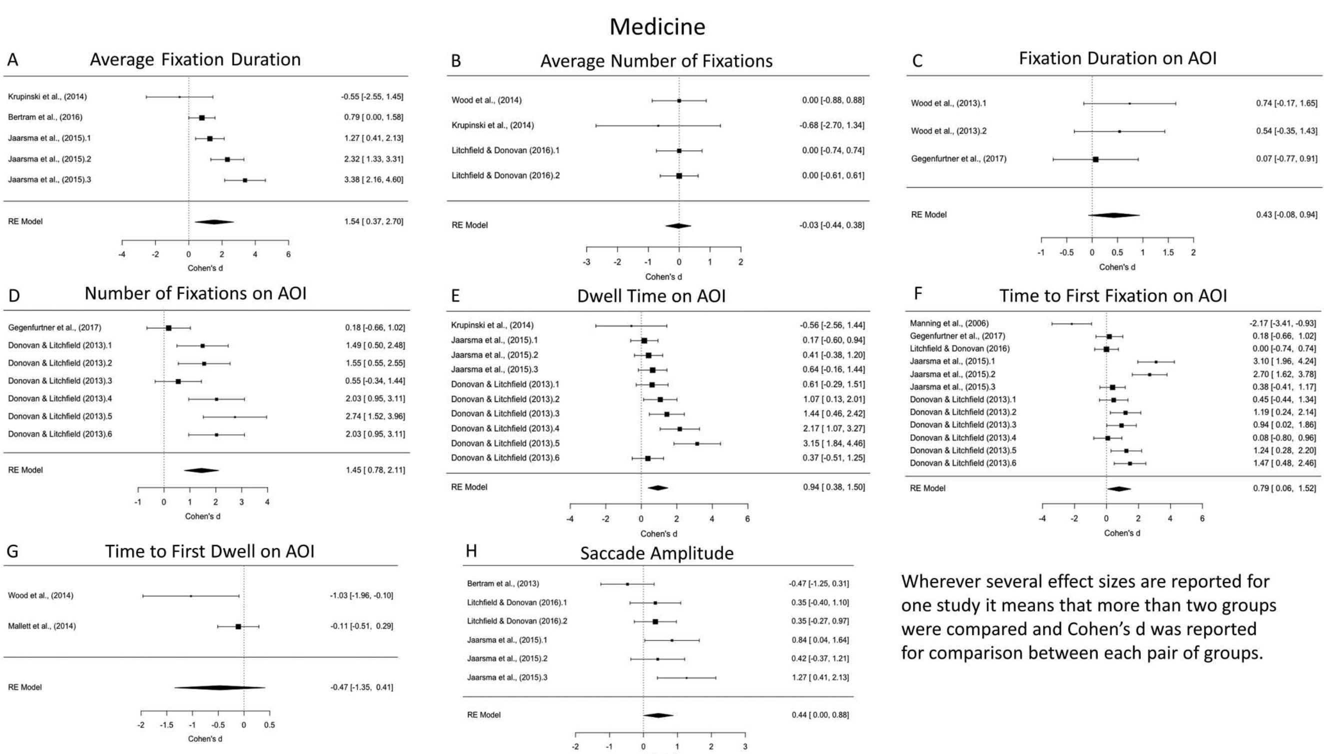

Figure 5. Eye-movement characteristics in medicine: (A) Average fixation duration. (B) Average number of fixations. (C) Fixation duration on AOI. (D) Number of fixations on AOI. (E) Dwell time on AOI. (F) Time to first fixation on AOI. (G) Time to first dwell on AOI. (H) Saccade amplitude.

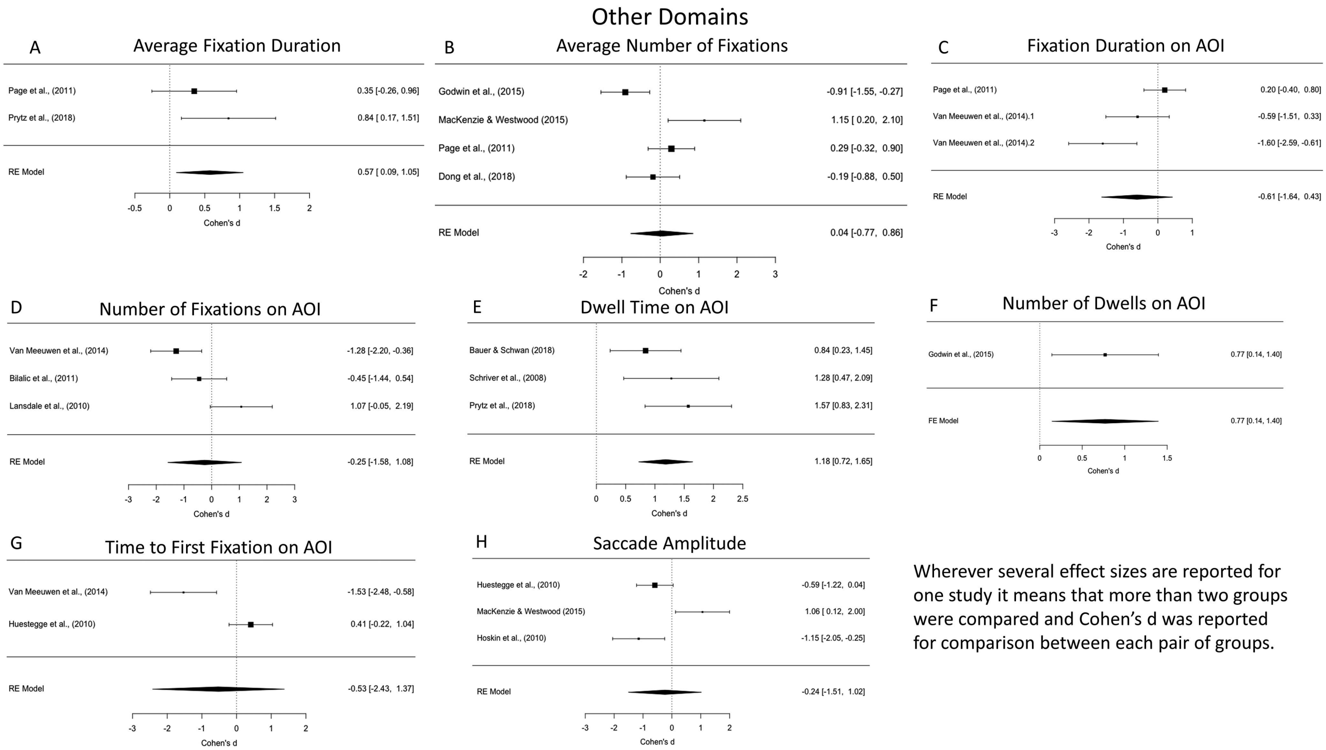

Figure 6. Eye-movement characteristics on other domains: (A) Average fixation duration. (B) Average number of fixations. (C) Fixation duration on AOI. (D) Number of fixations on AOI. (E) Dwell time on AOI. (F) Number of dwells on AOI. (G) Time to first fixation on AOI. (H) Saccade amplitude.

anticipation task. Skilled players used significantly more fixations of shorter duration and toward a greater number of locations when interacting with the far task, whereas visual search rate significantly decreased (i.e., fewer fixations) during the near task when whole field inspection was not necessary. No changes in visual search rate as a function of task were observed in the less-skilled group.

Furthermore, a publication bias analysis was conducted for the fixation duration, number of fixations and number of fixation locations separately. Although Egger's test was found significant for fixation duration ($z = 2.14$; $p = .03$); outcomes of both the trim-and-fill method (result: no missing studies in the funnel plot) as well as the fail-safe test (result: 289 studies needed to refute the results for the average fixation duration) suggested that publication bias was minimal or absent (Figure 2D). For the number of fixations and number of fixation locations Egger's test was nonsignificant ($z = -1.60$; $p = .11$; $z = -1.35$; $p = .18$) suggesting symmetry in the funnel plots (Figure 2E and 2F). The trim-and-fill method suggested no missing studies in these funnel plots. Finally, the fail-safe test indicated that at least 52 studies should be conducted to refute results for the average number of fixations and zero studies would be needed to refute results for number of fixation locations. This last result is to be expected, because weighted mean effect size analysis already reported no effect for the number of fixation locations ($\bar{d} = .02$; Table 9 and Figure 2C).

In summary, measures of search rate are related to the long-term working memory theory (Gegenfurtner et al., 2011), because the length and number of fixations are influenced by the processing speed of the brain, which, in turn, depends on the information available in the working memory. Although effects sizes were mostly medium or large, the direction of those effects varied between studies. These variations may be related to the tasks performed. Yet, we cannot conclude that this theory supports expert performance in sports based on these data alone. It is possible that these data can be explained in conjunction with other measures (see Multiple Gaze Features section below).

Selective Attention Allocation

In 31 of the 36 studies assessing expertise in sports, variables such as number and/or duration of fixations/dwells on AOIs were used as measures of selective attention allocation. In 25 of the 31 studies, experts tended to fixate or dwell more and/or make longer fixations or dwells on relevant AOIs, possibly ignoring salient irrelevant regions, compared with novices or intermediates. Effect size analyses showed moderate to large effects for these measures as predictors for expertise in most studies (Figure 3A and 3B). Williams and Davids (1998) did not report significant differences. However, the combination of a relatively small sample size (12 experienced and 12 less experienced soccer players) and a large effect size ($d = 1.08$) for fixation duration on the AOI (hip region in this case) suggests that this is a highly effective predictor for expertise in one-against-one soccer situations (Figure 3A). Finally, two studies reported fewer or shorter fixations on AOIs in experts compared with nonexperts (see Table 6). In the four remaining studies, no differences in selective attention allocation were re-

Table 9
Weighted Mean Effect Sizes (Cohen's d) for Each Gaze Feature Over the Domains of Expertise

	Visual search rate											
	Average fixation duration			Average number of fixations			Average number of locations fixated					
Domain	No. of studies	Weighted mean effect size	95% CI	No. of studies	Weighted mean effect size	95% CI	No. of studies	Weighted mean effect size	95% CI			
Sports	23	.45	[.12, .78]	22	.17	[−.38, .72]	10	.02	[−.38, .72]			
Medicine	3	1.54	[.40, 2.70]	3	−.03	[−.44, .38]						
Other	2	.57	[.09, 1.05]	4	.04	[−.77, .86]						
	Selective attention allocation											
	Average fixation duration on AOI			Average number of fixations on AOI			Average dwell time on AOI			Average number of dwells on AOI		
	No. of studies	Weighted mean effect size	95% CI	No. of studies	Weighted mean effect size	95% CI	No. of studies	Weighted mean effect size	95% CI	No. of studies	Weighted mean effect size	95% CI
Sports	18	1.01	[.76, 1.25]	10	1.08	[.64, 1.52]						
Medicine	2	.43	[−.08, .94]	2	1.45	[.78, 2.11]	3	.94	[.38, 1.50]	1	1.03	[.09, 1.98]
Other	2	−.61	[−1.64, .43]	3	−.25	[−1.58, 1.08]	3	1.18	[.72, 1.65]	1	.77	[.14, 1.40]
	Visual span											
	Time to first fixation on AOI			Time to first dwell on AOI			Saccade amplitude					
	No. of studies	Weighted mean effect size	95% CI	No. of studies	Weighted mean effect size	95% CI	No. of studies	Weighted mean effect size	95% CI			
Sports							2	1.08	[.64, 1.52]			
Medicine	5	.79	[.06, 1.52]	2	−.47	[−1.35, .41]	3	.44	[.00, .88]			
Other	2	−.53	[−2.43, 1.37]				3	−.24	[−1.51, 1.02]			

ported between expertise groups (see Table 6). However, two of these studies reported large effect sizes and the other two studies reported small effect sizes for eye-movement characteristics indicating selective attention allocation (Figure 3A and 3B).

Furthermore, a publication bias analysis was conducted for fixation duration on AOI. Egger's test was nonsignificant (z = 1.58; p = .12), suggesting symmetry in the funnel plot (Figure 3C). The trim-and-fill method also suggested no missing studies in the funnel plot. Finally, a fail-safe test indicated that at least 990 studies should be conducted to refute the results for fixation duration on AOI.

In summary, weighted mean effect sizes were high for fixation duration on AOI ($\bar{d}$ = 1.01) and number of fixations on AOI ($\bar{d}$ = 1.08; see Table 9), and eye-tracking measures indicate more selective attention allocation in experts. Taken together, these results support the information-reduction hypothesis (Gegenfurtner et al., 2011).

Visual Span

The eye-movement characteristics that were associated with visual span [that is, time to first fixation on relevant AOI (n = 1) and saccade amplitude (n = 4)] were examined in five of the 36 studies (see Table 6). Wu et al. (2013) compared novices and expert basketball players and showed a shorter time to first fixation on the relevant AOI for completion of nonexplicit anticipation tasks (i.e., predict the outcome of free throw attempts). Expertise related differences in saccade amplitude were reported in only one study (Cohen's d = .67), whereas the other three studies showed no difference and small effect sizes for saccade amplitude between experts and nonexperts (Figure 4A). Ryu et al. (2015) reported shorter saccade amplitudes in experts, compared with nonexperts, during performance of maximizing-optimizing decision task in which they had to decide which player was best placed to receive a pass.

In summary, the relatively scarce data on visual span does not support the holistic model of image perception as being relevant to expertise in sports.

Systematic Scan Pattern

In six of the 36 studies included, systematic scan patterns were reported in the group with the highest level of expertise (see Table 6). Effect sizes for experts using systematic scan patterns were moderate (Williams et al., 2002) to large (Vaeyens, Lenoir, Williams, & Philippaerts, 2007; Williams & Davids, 1998; Figure 4B).

Scan pattern systematicity is rarely assessed, so we cannot draw final conclusions about differences between experts and nonexperts. However, the above-mentioned analyses seem promising and indicate that scan pattern systematicity might be an effective predictor for expertise in sports.

Multiple Gaze Features

Multiple gaze features in experts were reported in 15 of the 36 studies reviewed and included, for the most part, an interplay between search rate and selective attention allocation to relevant AOIs (see Table 6). The combination of a faster search rate and selective attention allocation was observed in (optimizing-maximizing or nonexplicit) anticipation tasks or decision tasks (see Table 6). In contrast, a slower visual search rate in combination with selective attention allocation, was observed in a maximizing anticipation, optimizing decision/detection or optimizing-maximizing decision and nonexplicit tasks (see Table 6).

Various combinations of systematic scan patterns and different gaze features were observed in all six studies reporting systematic scan patterns in experts. The use of systematic scan patterns by experts was accompanied by a difference in selective attention allocation on specific AOIs (all six studies) and/or a difference in visual search rate compared with nonexperts (four of the six studies; Table 6).

In summary, it appears that several interactions between gaze characteristics related to search rate, selective attention allocation, and scan systematicity may explain expert performance. Although the most prominent interaction appears to be the one between search rate and selective attention allocation, it is still not clear what is the magnitude and direction of the relevant gaze features that are the basis for this finding.

Expert Performance and Gaze Features in Medicine-Related Domains

Performance. For performance measures in medicine, only three of the 19 studies (Tables 4 and 7) reported no group differences in accuracy between experts and nonexperts. In all other studies, experts outperformed nonexperts.

Gaze features. Figure 5 present forest plots and weighted average effect sizes for all eye-movement characteristics in medicine. In general, moderate to large weighted mean effect sizes were found for the average fixation duration, dwell time on AOI, number of fixations on AOI, time to first fixation on AOI and saccade amplitude.

Differences in one or more gaze features between experts and nonexperts (and/or intermediates) were reported in all studies except two (see Table 7). In these two studies, experts did not show superior performance compared with nonexperts. Expertise-related changes in gaze features as function of task and performance measures are discussed next (see Table 7).

Visual Search Rate

The eye-movement characteristics that were associated with visual search rate were examined in 10 of the 19 studies. In five of these studies, no differences were reported in visual search rate between experts and nonexperts (see Table 7). The effect size analyses revealed no effect for the number of fixations in two studies and a moderate effect for fixation duration in one study (Figure 5A and 5B). In five studies, differences in visual search rate were reported (see Table 7). When compared with nonexperts or trainees, experts made fewer fixations during task completion. In the study of Krupinski et al. (2014), the slower search rate (d = .68) in experts was observed in combination with shorter fixation durations (d = .55), resulting in a shorter total viewing time (Figure 5A and 5B). Finally, Bertram et al. (2016) reported an adapted visual search rate only in experts depending on task conditions (e.g., the image presentation rate in radiology). A higher presentation rate was related to longer fixation durations and a lower presentation rate was related to shorter fixation durations.

In summary, all five studies reporting differences in visual search rate between experts and nonexperts suggest a slower visual search rate in experts in medicine. However, because of the scarcity of data, we cannot say whether the long-term working memory theory solely explains the results.

Selective Attention Allocation

The eye-movement characteristics underlying differences in selective attention allocation between experts and novices were examined in 13 of the 19 studies. Significant differences between expertise group in fixation duration/dwell time on AOIs and/or number of fixations/dwells to AOIs were reported in all but one study (Schulte-Mecklenbeck et al., 2017). However, contradictory results, even within the same expertise domain, were reported in different studies for these characteristics. Specifically, in six studies experts fixated more and/or made longer fixations or dwells on relevant AOIs, suggesting that they were able to ignore irrelevant or salient regions compared with novices or intermediates (see Table 7). In these studies, large weighted mean effect sizes were reported for number of fixations and dwell time on AOI (Figure 5D and 5E).

Finally, Nodine, Kundel, Lauver, and Toto (1996) examined attention deviation due to salient areas in mammography lesion detection. Salient areas were defined as brighter spots on the mammograph without further meaning. The less experienced participants were mostly attracted by these irrelevant salient regions, whereas experts were able to disregard these features.

For the remaining six studies assessing selective attention allocation (see Table 7), opposite or inconsistent trends were reported (i.e., expert showed shorter fixation durations or dwell times or made fewer fixations on relevant AOIs as compared with novices or intermediates).

In summary, the data suggest that the number of fixations on AOI ($\bar{d}$ = 1.45) and dwell duration on AOI ($\bar{d}$ = .94) are effective predictors of expertise (see Table 9). Our conflicting results prevent us from suggesting the information-reduction hypothesis as the theory that explains expertise in medicine.

Visual Span

Two eye-movement characteristics were examined, namely, time to first fixation/dwell and saccade amplitude. A total of six studies examined time to first fixation/dwell on the AOI, five of which found a shorter time to first fixation/dwell and one reported a longer time to first fixation/dwell on AOI (see Table 7). Three studies reported a large effect and one study reported a small effect for the difference in time to first fixation or dwell on AOI between experts and nonexperts (Figure 5F and 5G).

Altogether, the saccade amplitude was examined in six studies. In three of these studies shorter saccade amplitudes were reported, whereas longer saccade amplitudes in experts compared with nonexperts were reported in one study. In the two remaining studies no differences were observed (see Table 7). An analysis of six effect sizes revealed a small to moderate weighted mean effect size ($\bar{d}$ = .44; Figure 5H).

In summary, these data suggest that time to first fixation may characterize experts in the medical domain. However, saccade amplitudes only characterize experts in medicine at a moderate level. These data provide partial support for the holistic model of image perception as a predictor of expert performance in medicine.

Systematic Scan Pattern

Altogether, four of the 19 studies assessing expertise in medicine, report systematic scan patterns in experts. Only one study provided descriptive statistics suggesting that systematic scan patterns are an efficient measure to predict expertise (see Table 7). Further research is needed on this topic.

Multiple Gaze Features

Multiple gaze features in experts were reported in 10 of the 19 studies and inconsistent trends in search strategy were observed across domains (see Table 7). However, because of the small number of studies and lack of consistent findings in these studies it was impossible to generalize about the use of particular search strategies adopted by experts in medicine-related domains.

Expert Performance and Gaze Features in Other Domains

Performance. For performance in other domains of expertise, only four out of the 18 studies assessed accuracy while not recording response or detection time (Tables 5 and 8). In all other studies, experts were more accurate than nonexperts. Response or detection time was measured in 12 of the 18 studies. In most of these studies, compared with nonexperts, experts had a shorter response or detection time. In one study, no difference was observed between the groups and in two studies longer response or detection times were reported in experts (Tables 5 and 8).

Gaze features. Figure 6 represents forest plots showing effect sizes and weighted averages for different eye-movement characteristics in other domains. In general, large weighted mean effect sizes were found for the average fixation duration, dwell time and number of dwells on AOI (Figure 6A, 6E, and 6F).

In most studies significant differences in one or more gaze features between experts and nonexperts (and/or intermediates) were reported. Only two studies did not report any significant effect of expertise on one or more gaze features (see Table 8). However, in one of those studies high effect sizes were reported for differences in saccade amplitude and average number of fixations between experts and nonexperts (MacKenzie & Westwood, 2015; Figure 6B and 6H). This finding might reflect low statistical power in these studies. The expertise-related changes in gaze features as a function of task and performance measures are discussed next (see Table 8).

Visual Search Rate

The eye-movement characteristics associated with visual search rate were studied in 10 of the 18 studies assessing various domains of expertise. In five of these studies no difference in visual search rate were reported between experts and nonexperts (see Table 8). Of the other five studies, four found a lower total number of fixations (Dong, Zheng, Liu, & Meng, 2018 [d = .19]; Francuz, Zaniewski, Augustynowicz, Kopiś, & Jankowski, 2018 [N/A]; Godwin et al., 2015 [d = .91]; Reingold, Charness, Pomplun, &

Stampe, 2001 [$d = .32$]). These results suggest that a slower visual search rate characterizes search strategy during task completion in experts. In the study of Prytz, Norén, and Jonson (2018), an approximately equal number of fixations was found in all groups during task completion, but experts showed longer fixation durations ($d = .84$; see Figure 2).

In summary, the conflicting results prevent us from suggesting that the long-term working memory hypothesis alone can explain expert performance in various domains. However, the fact that when differences were found they were consistent (lower total number of fixations) is promising and future work should explore this further.

Selective Attention Allocation

Various measures to assess selective attention allocation were collected in 16 of the 18 studies assessing expertise across domains. No differences between groups were reported for these measures in only three of the 16 studies (see Table 8). Most studies reported more and/or longer fixations/dwells on relevant areas (Bilalić et al., 2011, Reingold et al., 2001, and Van Meeuwen et al., 2014 are exceptions). Effect sizes for the dwell time on AOI and the number of dwells on AOI were generally large (Figure 6E and 6F).

Bilalić et al. (2011) and Reingold et al. (2001) assessed expertise in chess. Findings suggest that experts focus more on the middle of the board instead of on the individual chess pieces, which suggests that experts retrieve information concerning the chess pieces using the parafovea. The same tactic may have been used by the air traffic controllers in the study by van Meeuwen et al. (2014). Participants were asked to decide about the best order of arrival. All fixated less and for shorter durations on the aircrafts and the Artip (a point through which the aircraft has to pass before beginning an instrument landing approach) while completing this task.

In summary, dwell duration on AOI ($\bar{d} = 1.18$) and number of dwells on AOI ($\bar{d} = .77$) were put forward as strong predictors for expertise in other domains (see Table 9). Altogether, these data suggest that the information-reduction hypothesis may be able to explain differences in expertise in various domains.

Visual Span

The eye-movement characteristics analyzing differences in visual span between experts and nonexperts were conducted in eight studies. Altogether, two of these eight studies did not report any difference in visual span between groups. In the studies reporting differences between experts and nonexperts, expertise effects were observed for the time to first fixation/dwell as well as for the saccade amplitudes. In the study of Dong et al. (2018), experts were faster in fixating the marked area on a geographic map and in the study of van Meeuwen et al. (2014) experts were faster in fixating on the aircraft ($d = 1.53$). Contradictory results were observed in the study of Sheridan and Reingold (2014). In this latter study, a longer time to first dwell on the chess piece was reported in chess experts. These results concerning the time to first fixation/dwell on the AOI argue for an extended visual span in experts in geography and air-traffic controlling, but not in chess (see Table 8).

A total of three studies reported differences in saccade amplitudes between experts and nonexperts (see Table 8). However, these studies reported the opposite outcomes for saccade amplitudes in experts. The longer saccade amplitudes found in chess experts in the study of Reingold et al. (2001) suggest an extended visual span in this group, whereas the shorter saccade amplitudes in experts in driving in the studies of Hosking et al. (2010) and Huestegge, Skottke, Anders, Müsseler, and Debus (2010) suggest a more thorough search conducted by experts to assess hazardous situations. In general, studies assessing expertise in driving argue for a higher central focus in expert drivers instead of a wide visual scanning behavior in hazardous situations. Because expert drivers develop visual strategies that can adapt to specific demands of the traffic situation, we cannot draw final conclusions concerning general differences in visual span between novice and expert drivers based on the results of these two studies using hazardous driving situations (e.g., Borowsky, Shinar, & Oron-Gilad, 2010; Crundall, Chapman, Phelps, & Underwood, 2003).

The effect sizes for differences in saccade amplitude between experts and nonexperts were large and moderate (Figure 6H). In chess, the long saccade amplitudes, alongside the above-mentioned observation that experts fixate less on chess pieces, may suggest that parafoveal information processing due to an extended visual span, developed with expertise.

In summary, the above-mentioned results suggest an extended visual span in experts in chess, air-traffic controlling, and geography, which is in line with the holistic model of image perception. However, because of some conflicting results and the relatively small number of studies assessing the visual span in experts we have to interpret these results carefully and future work should explore this further.

Systematic Scan Pattern

Only two of the 18 studies reported systematic scanning behavior in experts, one in analyzing proton-nuclear-magnetic resonance (proton-NMR) spectra and one in air-traffic controlling (ATC; Table 8). During proton-NMR spectra analysis, experts only scanned between the NMR-signals and the correct answer, whereas nonexperts scanned between all areas on the display (e.g., distractor structures, white space, question stem, etc.) indicating a more chaotic scanning behavior in the nonexpert group (Topczewski, Topczewski, Tang, Kendhammer, & Pienta, 2017). In ATC, the scan patterns used by experts suggest a working-forward rather than means-end strategy. They showed fewer transitions that included the destination point of the aircraft (i.e., Artip-aircraft and Artip-background) than novices. This finding indicates that novices frequently focus on the goal to reach a solution, whereas experts develop a solution without paying attention to the goal (van Meeuwen et al., 2014). In both domains, experts seemed to use more simplified patterns compared with nonexperts.

Because of the small number of studies assessing systematic scanning and the lack of statistics to analyze effect sizes, it is not possible to draw final conclusions about systematic scanning in experts in these domains.

Multiple Gaze Features

A total of seven of the 18 studies assessing expertise in other domains report eye-movement characteristics that underlie multiple gaze features. The results were inconsistent (for details, see Table 8). In sum, a variety of gaze features combinations were observed in different expertise domains. We cannot draw final conclusions about which combination is the most suitable to obtain expert performance.

Associations Between Superior Perceptual-Cognitive Task Performance and Eye-Movement Characteristics in Experts

The direct assessment of the associations between gaze features and performance outcome measures were available in only 12 of the 73 included studies: five in sport-related domains (see Table 3), three in medicine-related domains (see Table 4), and four in other domains of expertise (see Table 5). Wood et al. (2013) reported that, among radiologists, a shorter time to first fixation on a fracture was significantly correlated with higher rates of correct diagnosis. Francuz et al. (2018); Milazzo, Farrow, Ruffault, and Fournier (2016), and Piras, Lobietti, and Squatrito (2014) revealed: (a) positive correlations between a slower search rate and accuracy and/or (b) negative correlation between a faster search rate and decision/reaction time (RT). In contrast, Krupinski (1996), reported that longer gaze durations (suggesting a slower search rate) were related to false-negative decisions in mammography lesion detection.

In addition, Topczewski et al. (2017) reported that novices who performed better used less time to complete a scan pattern compared with novices that performed worse. In these two cases, faster search rates were related to higher accuracy in examining mammography's and proton-nuclear-magnetic resonance (proton-NMR) spectra. Schulte-Mecklenbeck et al. (2017) reported a relationship between longer dwell times on diagnostic cues and a higher accuracy. This relationship between longer dwell/fixation times and a higher accuracy has been reported in sport (see Table 6) and aviation (Schriver, Morrow, Wickens, & Talleur, 2008).

In summary, although not causal, the presence of relationships between experts' eye movement characteristics and their performance support the notion that gaze behavior is related to expert performance.

Discussion

In the current review, we aimed to unravel the visual search processes that may explain superior performance on perceptual-cognitive tasks in experts. Moreover, we attempted to identify theories that highlight these processes within specific domains of expertise. We attempted to answer three questions: (a) Which types of eye-movement characteristics best predict expertise and what is their relation to superior performance on perceptual-cognitive tasks?; (b) To what extent does systematic scanning predict expertise and superior performance on perceptual-cognitive tasks?; and (c) Can gaze features and the related theories be generalized across different domains of expertise and tasks?

Overall, measures for the number and duration of fixations/dwells on AOIs were included in most studies of expertise, across the different domains. The findings showed longer and/or more fixations/dwells on AOIs in experts, except in studies in the medical domain. In medicine, the results were more conflicting with half of the studies assessing these measures reporting a high number and/or duration of fixations/dwells on AOIs, whereas the other half reported the opposite. In addition, experts in medicine took less time to first fixate/dwell on the AOI. Some papers did not report differences in any eye-movement characteristic between experts and nonexperts (Casanova et al., 2013; Dyer, Found, & Rogers, 2008; Gorman et al., 2013; Hancock & Ste-Marie, 2013; Mackenzie & Westwood, 2015; Núñez et al., 2009; Page et al., 2011; Piras et al., 2014). However, in some of those studies large effect sizes were reported for specific eye-movement characteristics, whereas the absence of significant effects may reflect low statistical power. Furthermore, it is possible that differences in expert performance are not always manifest in differences in visual search behavior, with instead experts being better purely due to the information retrieved from memory. Finally, we found evidence linking specific gaze features and systematic scanning across all domains of expertise.

The key differences and similarities of gaze features used by experts, the relationship between gaze data and performance, and the different theories explaining specific gaze behavior in experts are discussed next.

Gaze Features Related to Expertise

Visual search rate. The visual search rate differed between experts and nonexperts, although the direction of change was not consistent. In some studies, compared with nonexperts, experts made fewer fixations indicating a slower visual search rate. This effect was reported in 11 studies in sports (see Table 6), three studies in medicine (see Table 7), and four studies in other domains (art: Francuz et al., 2018; military: Godwin et al., 2015; chess: Reingold et al., 2001; and geography: Dong et al., 2018; see Table 8). In contrast, in nine studies across sports, experts made more fixations indicating a faster visual search rate (see Table 6). In medicine, as well as in some other domains, only static two-dimensional (2D) tasks were used in the studies assessing visual search rate. According to the meta-analysis conducted by Gegenfurtner et al. (2011), fewer fixations are expected in a 2D task performed by experts when compared with a three-dimensional (3D) task. This finding can be explained by the observation of Barrouillet and Camos (2007) and Mayer and Moreno (2003) that these types of tasks appear to be less demanding for the working memory compared with dynamic and/or 3D tasks. In sports, mostly 2D dynamic video clips were used. Although the findings involving sports are somewhat conflicting, it appears that visual search rate was related to the type of task.

In anticipation tasks, experts appeared to use mostly a faster visual search rate, whereas in decision or detection tasks, experts used a slower visual search rate. This finding is in line with those reported by Mann, Williams, Ward, and Janelle (2007) that expertise differences in the perceptual and decision-making strategies of athletes are task dependent. Also, a slower visual search rate in detection or decision tasks was reported in the meta-analysis of Gegenfurtner et al. (2011). Another explanation for slower visual search rates is the capability of experts to ignore irrelevant information, while acquiring relevant information to optimize their response or decision time on a perceptual-cognitive task (Pieters, Warlop, & Hartog, 1997). Ignoring irrelevant information would result in fewer fixations, as indicated by a slower visual search rate. This idea is similar to the information-reduction hypothesis discussed below and may help in detecting "low expectancy high value regions" (Wickens & McCarley, 2007, p. 50), which is of importance in medicine.

The high detection rates for nodules and other pathologies, which might appear in low expectancy regions, are of utmost important in this domain to optimize medical care. This finding might explain why only a slower visual search rate was observed in medicine, because in this domain accuracy is highly important. Furthermore, this strategy can explain the high prevalence of the combination of a slower visual search rate and a selective attention allocation, because irrelevant areas are ignored and relevant areas are fixated in this case. This is in line with Rayner's (1998) suggestion that a smaller number of fixations indicates a more efficient search process. Furthermore, the observation that shorter fixation durations and/or fewer fixations are sufficient for successful perceptual-cognitive task completion, suggests a fast information pick-up in experts. More specifically, experts have sufficient information in their long-term working memory due to experience that can be retrieved rapidly when specific tasks have to be completed, which is in line with the long-term working memory theory (Ericsson & Kintsch, 1995).

Finally, some researchers in sports have reported that experts switched between a high number of fixations and a low number of fixations indicating an adaptive visual search rate (Casanova et al., 2013; Laurent, Ward, Williams, & Ripoll, 2006; Roca et al., 2013; Uchida, Mizuguchi, Honda, & Kanosue, 2014). A possible explanation for the variety of visual search rate tactics in experts across different studies is the number of elements that have to be analyzed during the task (Casanova et al., 2013; Vaeyens et al., 2007; Williams & Davids, 1998). Experts appear to adapt their visual search rate according to the number of elements that require analysis better than nonexperts. Similar observations were reported in other domains. In aviation, for example, licensed pilots were shown to use more fixations during takeoff and landing (more elements to analyze) compared with cruise conditions (fewer elements to analyze), indicating a faster visual search rate (Brams et al., 2018; Di Nocera & Bolia, 2007). In medical imaging, the presence of nodules or lesions increase the number of elements that have to be analyzed. In such cases, experts adapt their visual search rate to a faster visual search rate (Bertram et al., 2013, 2016).

Selective attention allocation. Selective attention allocation was another gaze feature showing differences between experts and nonexperts in different domains of expertise. In general, most experts appear to make more fixations of longer durations on relevant AOIs, suggesting that they are better at selectively allocating their attention and ignoring irrelevant areas. This observation is in accordance with previous research showing enhanced selective attention processes in experts (e.g., Augustyniak & Tadeusiewicz, 2006; Bishop, Kuhn, & Maton, 2014; Vickers, 1992). Selective attention allocation is expected to be beneficial for perceptual-cognitive task completion because the amount of essential information processed is optimized. Experienced participants will systematically move their focus from one AOI to another, guided by experience or previous knowledge, which is in line with the *guided search* theory (Wolfe, 1994). Selective attention allocation has shown to be related to high accuracy scores, which is expected to be more important in medicine, as well as fast response or decision times, which is expected to be more important in sports. In all other domains of expertise, improved accuracy, and/or response time were accompanied by a high selective attention allocation. Overall, measures to assess attention allocation have been shown to be a good measure to assess expertise across domains. These findings support the information-reduction hypothesis, suggesting that experts are better at selectively attending to task-relevant information and ignoring task-irrelevant information (Haider & Frensch, 1999). However, results from seven of the studies in the present review contradict the information-reduction hypothesis (two in sports: Table 6; four in medicine: Table 7; two in chess: Table 8; and one in air traffic control: Table 8). In these studies, experts made fewer fixations/dwells of shorter durations/dwell times on the relevant region. A possible explanation for this contradiction is the development of an extended visual span in experts.

Visual span. An extended visual span is essential for a global-local search and is observed as a shorter time to first fixate a relevant AOI and by longer saccade amplitudes. During the global search, experts are assumed to extract essential information from their para-foveal vision (Bertram et al., 2013; Kundel & Nodine, 1975) and capture essential information, which is examined in detail during a local scan. Consequently, because this local scan is the second time information is processed, shorter fixation durations might be enough. This finding suggests that experts using an extended visual span were more accurate on the specific task as a result of double checking (first check during global search; second check during local search) of relevant AOIs (Leong et al., 2007).

There exists evidence for better para-foveal information processing capabilities, and thus an extended visual span, in experts across several domains of expertise. In studies assessing para-foveal information processing, specific foveal blurred scenes were used during task completion (e.g., Fox, Merwin, Marsh, McConkie, & Kramer, 1996; Ryu et al., 2015). Ryu et al. (2015) provide evidence for a fluent switch between para-foveal and foveal information processing in experts, as experts were more successful when the para-foveal view was blocked. Further evidence for use of para-foveal information processing in experts was put forward by Fox et al. (1996) who examined flight performance in highly experienced and less experienced pilots by showing that performance of highly experienced pilots decreased more when para-foveal vision was blocked compared with less experienced pilots. Yet, studies addressing para-foveal information processing in experts are scarce and further empirical work is necessary.

In other domains, an extended visual span appeared to be related to expertise. In air traffic controlling (van Meeuwen et al., 2014) and geography (Dong et al., 2018), a shorter latency to first fixate the AOI was observed in experts. This finding may indicate that in these two domains experts already capture the scene globally during the preattentive phase (Kundel & Nodine, 1975), which rapidly guides them to the AOI during the local scan. In contrast, in hazard detection tasks in motor riding (Hosking et al., 2010) and car driving (Huestegge et al., 2010), more experienced drivers that used shorter saccade amplitudes were more successful. In driving, the focus of expansion (FOE) is identified as a point on the horizon where drivers focus on and an optic flow expands from it toward the vehicle. When the fovea of the eye is directed at the focus of expansion, optic flow can be detected in the peripheral part of the eye's retina. This point is identified as the most important one to focus on for optimal monitoring of changes in the pattern of optic flow. Strong deviations from this point can result in unsafe driving (Mourant, Ahmad, Jaeger, & Lin, 2007). This finding could explain why short saccade amplitudes are beneficial for hazard detection in driving tasks.

Overall, these findings partly support the hypothesis that experts have an extended visual span that allows them to first globally analyze a scene by using their para-foveal vision. Stronger evidence for a visual span was observed in medicine compared with the other domains of expertise. These results tend to be in line with the hypothesis of the holistic model of image processing (Kundel et al., 2007).

Systematic Scanning Related to Expertise

In general, experts appeared to follow a more structured scan pattern that linked different AOIs. Scan pattern systematicity has been shown to be beneficial for both decision time and accuracy. A recent review suggested that systematic scanning has beneficial effects on accuracy in lung tumor detection in radiology and that 30% of the missed lung tumors were due to unsystematic scanning (del Ciello et al., 2017). Other findings suggest that systematic scanning can optimize selective attention allocation and facilitate pick-up of essential information, resulting in enhanced performance (Megaw & Richardson, 1979), which could explain the high prevalence of a combination of a high selective attention and systematic scanning in the eye-tracking results in some of the reviewed studies (e.g., Crespi et al., 2012; O'Neill et al., 2011; Ripoll, Kerlirzin, Stein, & Reine, 1995; Topczewski et al., 2017; Vaeyens et al., 2007; Williams et al., 2002; Williams & Davids, 1998). There exists evidence to support relationships between systematic scanning and expertise across a wide variety of domains (e.g., in aviation: Bellenkes, Wickens, & Kramer, 1997 and Fitts & Jones, 1947; in medical imaging: Kundel & La Follette, 1972; ECG reading: Augustyniak & Tadeusiewicz, 2006; in visual inspection of small integrated circuits: Schoonahd, Gould, & Miller, 1973). It has also been shown that visual scan strategies can be taught and that a better adaptation to more systematic visual scan pattern is related to enhanced performance (Czaja & Drury, 1981; Sadasivan, Greenstein, Gramopadhye, & Duchowski, 2005; Vitak, Ingram, Duchowski, Ellis, & Gramopadhye, 2012; Wang, Lin, & Drury, 1997). Although the data are limited, it appears that systematic scanning is related to expert performance.

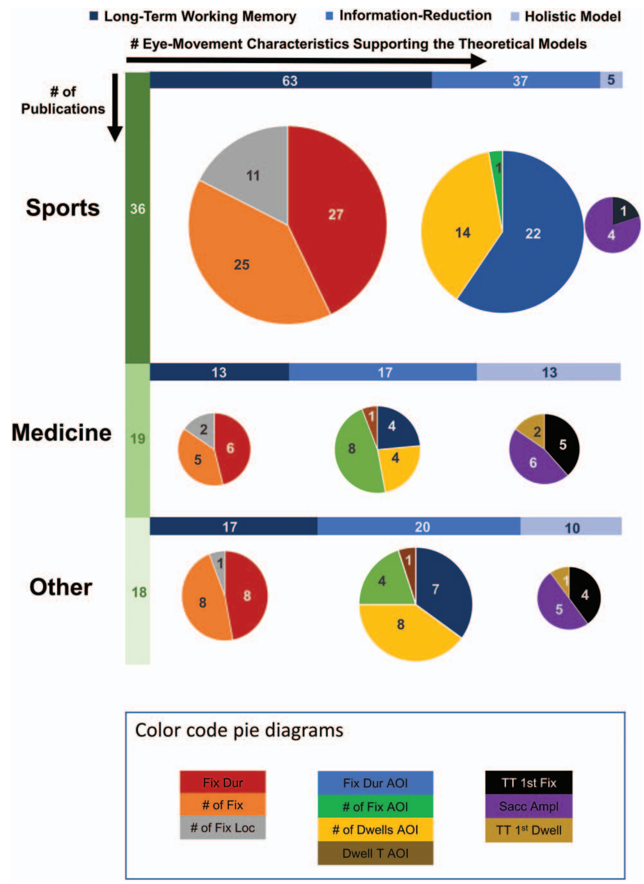

Figure 7. Spread of eye-movement characteristics (Fix Dur = fixation duration; # of Fix = number of fixations; # of Fix Loc = number of fixation locations; Fix Dur AOI = fixation duration on the AOI; # of Fix AOI = number of fixations on the AOI; # of dwells AOI = Number of dwells on the AOI; Dwell T AOI = dwell time on the AOI; TT 1st Fix = time to first fixation on the AOI; Sacc Ampl = saccade amplitude; TT 1st dwell = time to first dwell on the AOI) analyzed within one domain of expertise (# of Publications = number of publications) that support one of the three theories of perceptual-cognitive expertise (# Eye-Movement Characteristics Supporting the Theoretical Models = number of eye-movement-characteristics supporting the theoretical models). See the online article for the color version of this figure.

Suggestions for Future Research

In general, the summaries of all relevant papers from different expertise domains prevent us from drawing final conclusions about the way in which the gaze features support the different theories about viewing strategies and attention allocation across all areas of expertise. This conclusion is attributable, at least in part, to the skewness of the analyses conducted in each specific domain (see Figure 7). What is very clear from Figure 7 is that the different theories are not equally dominant in each domain of expertise, and that the use of different gaze features often goes hand in hand with specific theoretical assumptions in each domain.

Theoretically, it would have been possible to observe strong correlations between different gaze features across different areas of expertise, and perhaps also strong convergence between the different theories. In principle, one could envisage a scenario of expertise development which is common to all domains of expertise, in which the different components of expertise that are highlighted in the different theories would go hand-in-hand. Information processing could be optimized by (a) selectively allocating the available attentional resources to task relevant stimuli and ignoring irrelevant stimuli (i.e., the information-reduction hypothesis), resulting in longer durations and more fixations on relevant areas and shorter durations and less fixations on distractor areas; or (b) extracting visual information from distal and para-foveal regions, allowing more efficient global-local processing of the scene (i.e., the holistic model of image perception), resulting in a shorter time to initially fixate the relevant area and longer saccade amplitudes, reflecting an extended visual span and more global scene processing; or (c) relying more on the encoding and retrieval of visual information from long-term working memory (i.e., the long-term working memory theory), resulting in shorter and less fixations irrespective of location.

Alternatively, it is equally well possible that each domain of expertise leads to its own trajectory of information-processing optimization because each set of domain-specific stimuli and its associated processing demands is different, which would lead to more specialized ways of attending and selecting information, showing little commonality between domains of expertise. For instance, information-reduction could be strongest in situations where experts need to deal with quickly moving, complex stimuli, such as dynamic ball sports, whereas holistic perception and great benefits from quickly activating stored templates from long-term memory are more likely to occur in situations with visually similar images such as X-rays of chests. Unfortunately, we cannot disentangle these distinct possibilities because dominant theories, frequently extracted gaze features, and domains of expertise are presently strongly confounded in the literature (see Figure 7).

We suggest avenues for future research. First, in future researchers should try to evaluate a broader range of gaze features to account for all possible theories of enhanced information processing and use similar measures as much as possible. More studies should try to formulate hypotheses from different potentially relevant theories instead of focusing on only one theory, which happens to be predominant in that domain of expertise. Second, there is a large variance in levels of expertise between studies. For example, in the study of Bertram et al. (2016) two years of experience in interpreting medical images is already sufficient to be implemented in the expert group, whereas in the study of Krupinski (1996), participants with three or four years of experience in interpreting medical images are included in the novice group. This variance hinders our ability to draw conclusions and/or to compare studies. We suggest that future studies should carefully chose their expertise groups to be able to compare their results to the literature. Finally, several eye-movement characteristics (e.g., systematic scan pattern, time to first fixation on AOI) were found to have large effects, but in a small number of studies. In future, researchers should try to replicate these effects in larger samples and in different areas of expertise.

Conclusions

The inconsistencies in the results of the studies included in this systematic review can prevents us from ruling unequivocally that some gaze features are better than others for experts in certain domains or tasks. The large amount of inconsistencies in this systematic review can mainly be explained by the wide variety of methodologies used across studies, for instance differences were observed in: (a) sample size; (b) level of expertise of the expert group (for a review, see Gegenfurtner et al., 2011); (c) the identified AOIs and time window (Brunyé, Mercan, Weaver, & Elmore, 2017; Donovan & Litchfield, 2013; Gegenfurtner et al., 2017; Jaarsma, Jarodzka, Nap, van Merriënboer, & Boshuizen, 2015; Manning, Ethell, Donovan, & Crawford, 2006); (d) recording and analysis methods for eye-tracking measures; (e) instructional sets (e.g., Kaakinen & Hyönä, 2010), (f) perspectives of the visual stimuli (first person, overhead, etc.), and (g) stimuli (e.g., moving, stationary). This variability in the methods employed should be addressed in future research. The largest inconsistency related to the task set-up, highlighting a need to determine the most efficient task set-up and to use such tasks consistently to improve the generalizability of the findings. An effective task set-up should be as realistic as possible and implement the use of essential perceptual-cognitive skills for the specific domain of expertise. The newest technologies like virtual reality can help create a first-person perspective of the task, thereby enhancing our ability to unravel the perceptual-cognitive skills that underlie superior performance in experts.

In conclusion, although there are inconsistencies in the results of the reviewed studies and the available data is scarce for some domains, the current review highlights the importance of an efficient visual search rate, enhanced selective attention allocation, an extended visual span, and scan pattern systematicity for expert performance in various domains of expertise. Moderate to large weighted mean effect sizes were observed for the differences between experts and nonexperts in: (a) average fixation duration, fixation duration on AOI, and systematic scan pattern in sports; (b) the average fixation duration, number of fixations on AOI, dwell time on AOI, time to first fixation on AOI, and saccade amplitude in medicine; and (c) the average fixation duration, dwell time, and number of dwells on AOI in other domains.

The gaze features related to the information-reduction hypothesis turn out to be more relevant in all domains of expertise, except for medicine, where the holistic model of image perception appears to be more important. Based on these findings, we can conclude that the development of expertise generally results in an enhanced ability to selectively locate attention on the most relevant areas, whereas only in medicine, expertise involves an extended visual span. Note, however, that all three theories or some combinations of these theories may explain some aspects of expert performance, depending on the specific task. The field is, therefore, in strong need of a more integrative theory, which encompasses the basic building blocks highlighted by each theory but with sufficient empirical support. More systematic research with comparable methods is also necessary to be able to draw more final conclusions about the exact theory that can best explain superior performance on perceptual-cognitive tasks across different domains of expertise. Finally, because specific gaze features as well as systematic scanning appear to facilitate expert performance, more application-oriented research should try to implement gaze training to improve performance in perceptual-cognitive tasks.

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