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The use of contextual priors and kinematic information during anticipation in sport: toward a Bayesian integration framework

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ABSTRACT

Expert performance across a range of domains is underpinned by superior perceptual-cognitive skills. Over the last five decades, researchers have provided evidence that experts can identify and interpret opponent kinematics more effectively than their less experienced counterparts. More recently, researchers have demonstrated that experts also use non-kinematic information, in this paper termed *contextual priors*, to inform their predictive judgments. While the body of literature in this area continues to grow exponentially, researchers have yet to develop an overarching theoretical framework that can predict and explain anticipatory behaviour and provide empirically testable hypotheses to guide future work. In this paper, we propose that researchers interested in anticipation in sport could adopt a Bayesian model for probabilistic inference as an overarching framework. We argue that athletes employ Bayesian reliability-based strategies in order to integrate contextual priors with evolving kinematic information during anticipation. We offer an insight into Bayesian theory and demonstrate how contemporary literature in sport psychology fits within this framework. We hope that the paper encourages researchers to engage with the Bayesian literature in order to provide greater insight into expert athletes' assimilation of various sources of information when anticipating the actions of others in complex and dynamic environments.

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Background

We are frequently required to make accurate estimates about the state of an uncertain world, often with only probabilistic information to hand (Brunswik, 1952). The ability to make predictive judgements about the world around us, often on the basis of ever-changing and partial information, is integral to skilled performance. Specifically, the ability to successfully anticipate what is likely to happen, before it actually occurs, is important

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when performing in dynamic and rapidly evolving environments, such as those encountered in many sports (Williams et al., 2011; Yarrow et al., 2009).

It is well established that expert athletes are superior to novices at utilising advance visual information – specifically, kinematic information emanating from an opponent’s biological motion – to inform their decisions (Williams & Jackson, 2019). However, in recent years, researchers have started to explore the use of non-kinematic sources of information, referred to in this paper as *contextual priors*, to enhance anticipation skill (Cañal-Bruland & Mann, 2015). In the quest for an overarching framework, it has been suggested that athletes may employ Bayesian reliability-based strategies in order to integrate contextual priors with evolving kinematic information during anticipation (Loffing & Cañal-Bruland, 2017). A Bayesian approach suggests that contextual priors are continuously combined with incoming environmental information to produce a joint estimate. The dependency on both information sources is modulated by the reliability of the information at hand and their respective temporal evolution (Körding, 2007). Furthermore, Bayesian theory postulates that people strive not only to increase the likelihood that their judgements will be accurate, but also to maximise the expected utility (i.e. cost/reward) of these judgements (Vilares & Körding, 2011).

In this paper, we examine how a Bayesian model for probabilistic inference could act as an overarching framework for anticipation in sport in the hope this will act as a catalyst for future research in the area. In the first section, we provide the reader with an overview of key empirical research and models focusing on the use of kinematic information and contextual priors in the domain of sport. In the second section, we provide an overview of Bayesian theory, drawing on research from domains such as healthcare and law enforcement, with the intention of demonstrating the suitability of this framework for explaining anticipation in sport. In section three, we utilise terminology from the Bayesian literature to discuss moderating factors that may impact anticipation.

Anticipation in sport

Anticipation has been described as the ability to recognise the outcome of others’ actions prior to and during the execution of those actions (Williams & Ford, 2013). In sport, and a wide range of other domains, such as law enforcement, surgery and the military, experts have consistently demonstrated the ability to anticipate upcoming actions more quickly and accurately than their less skilled counterparts (Williams & Jackson, 2019). In sport, the ability to anticipate accounts for more variance in performance than physical or physiological factors (Williams & Ford, 2008; Williams & Reilly, 2000). Thus far, researchers have identified that a number of different sources of information are used during anticipation in sport.

Kinematic information

While it is likely that information from other sensory modalities contributes to anticipation (e.g. auditory information; Cañal-Bruland et al., 2018), the sport literature has tended to focus on how athletes use visual information during anticipation. It is well established that athletes are able to pick up and use advance kinematic information, including information from equipment such as a baseball bat or a tennis ball, in order to predict

opponents' future actions. In a meta-analysis, Mann et al. (2007) reported that expert athletes have superior visual search strategies compared to novices that enables them to detect and utilise advance kinematic cues emanating from the opponent. Mobile eye tracking devices have commonly been used to characterise the visual search strategies of experts (Kredel et al., 2017). Savelsbergh et al. (2002) used gaze tracking to elucidate expert and novice soccer goalkeepers' anticipation of penalty kicks. Not only were the experts more accurate with their decisions, but this was also underpinned by more fixations on task-relevant cues such as placement of the non-kicking foot. An analysis of gaze data across various stages of the action revealed that the experts' processing priorities changed over time. The time spent fixating on the upper body decreased as the penalty taker approached the ball, and more time was devoted toward the legs and ball, which were more reliable cues to predict kick direction.

Point-of-gaze does not entirely reflect the athlete's allocation of attention, as covert attention to cues in the visual periphery is not picked up by eye movement registration systems (Mann & Savelsbergh, 2015; Vater et al., 2019). It has been shown that expert athletes also use peripheral vision more effectively than novices to inform anticipation (Schorer et al., 2013) and decision making (Ryu et al., 2013). A complementary measure, which provides additional insight into an athlete's processing priorities, is the collection of immediate retrospective verbal reports of the thought processes engaged in during task performance (Eccles, 2012; Ericsson & Simon, 1980). This technique is particularly advantageous when examining how athletes integrate kinematic and non-kinematic information during anticipation performance (see discussion later on).

Another technique that has been used to assess the impact of kinematic information during anticipation is progressive temporal occlusion. This technique requires the participant to respond to video stimuli that are occluded at various time points relative to the unfolding of the to-be-anticipated action (e.g. Farrow et al., 2005; Müller et al., 2009; Müller & Abernethy, 2006). Farrow et al. (2005) required expert and novice tennis players to predict the direction of oncoming serves. Both expert and novice players were more accurate when the video clips were occluded closer to racket-ball contact (i.e. when kinematic cues were highly reliable), compared to earlier occlusion points (i.e. when kinematic cues were less reliable). Furthermore, expert players detected pertinent kinematic information earlier than novices (see also, Loffing & Hagemann, 2014a; Wright et al., 2013). The authors also compared full-length videos whose duration varied across occlusion conditions, to moving windows that captured different phases of the service action but where the durations of the video clips were constant across conditions, thereby standardising the amount of kinematic information available. The reliability of kinematic information – manifested in its impact on response accuracy – was not modulated by the total amount of kinematic information available prior to occlusion, but rather by the informativeness of the server's kinematics regarding serve direction (Farrow et al., 2005).

A model for integrating kinematic information

Müller and Abernethy (2012) created a model to predict the anticipatory processes of expert and novice athletes in striking sports (see also Morris-Binelli & Müller, 2017). When tasked with anticipating and intercepting opponents' actions, athletes' processing priorities fluctuate according to the task-relevance of informational variables to hand; as

unfolding kinematic cues become more relevant to task performance, and therefore a more reliable predictor of the forthcoming action, athletes refine their anticipatory judgements correspondingly. The model predicts that, since expert athletes are more attuned to task-relevant information, they can infer the reliability of evolving kinematic information quickly and accurately, adjusting their priorities accordingly and enhancing performance.

The model provided an initial discussion in to the integration of kinematic information during anticipation in striking sports, but the sport-specific and linear nature of the model restricts its applicability to broader performance settings, including highly dynamic and information-rich environments in which information sources may interact in a non-linear fashion. Moreover, while Müller and Abernethy (2012) highlighted that a priori probabilistic information, in the form of expectations and beliefs, are likely to influence athletes' anticipatory processes, the model did not include detail in to this factor given the limited understanding at this time of how such information is used by athletes. In recent years there has been a broadening of focus when examining anticipation in sport to include the impact of non-kinematic sources of information (Cañal-Bruland & Mann, 2015).

Contextual priors

Scientists have demonstrated that expert anticipators outperform novices in the absence of reliable kinematic information. A seminal paper by Abernethy et al. (2001) demonstrated that expert squash players performed better than chance, and superior to less-skilled players, when vision was occluded prior to any significant pre-contact movement by the opposing player. The authors suggested that experts could use *situational probabilities* to inform their anticipatory judgements. In the next decade or so, the majority of research remained focused on the use of kinematic information, leading Cañal-Bruland and Mann (2015) to call for researchers to broaden their scope and examine the role of probabilistic information. The authors used the phrase *contextual information*, suggesting the term is interchangeable with situational probability, which has caused some confusion with terminology in the literature. On closer inspection of subsequent papers in the area, it appears that the term 'contextual information' is used broadly to capture a range of non-kinematic sources of information that are identified and interpreted in the light of domain-specific knowledge and consequently change the situational probabilities – ultimately improving anticipation performance. Importantly though, these contextual sources of information are available *prior* to any reliable kinematic information pertaining to the final action. With this in mind, and in line with the terminology used in the Bayesian literature (see discussion later on), we use the term *contextual priors* in this paper to refer to any non-kinematic source of information that is utilised through domain-specific knowledge and enables a sophisticated understanding of situational probabilities. Contextual priors include, but are not limited to, match status (e.g. Farrow & Reid, 2012), opponent positioning (e.g. Loffing & Hagemann, 2014b; Murphy et al., 2016; Runswick et al., 2017), patterns of play (e.g. Loffing et al., 2015; McRobert et al., 2011), opponent action tendencies (e.g. Gredin et al., 2018; Mann et al., 2014), coach instructions and tactics (e.g. Crognier & Féry, 2005; Levi & Jackson, 2018), and

weather and surface conditions (e.g. Schläppi-Lienhard & Hossner, 2015; Vernon et al., 2018).

Contextual priors can be *stable* during the unfolding action, as they are established before the action commences and remain unchanged throughout its time course, such as opponent action tendencies (Broadbent et al., 2018; Gray, 2015; Gray & Cañal-Bruland, 2018; Gredin et al., 2018; 2019; 2020a; 2020b; Helm et al., 2020; Loffing et al., 2015; Lüders et al., 2020; Mann et al., 2014; Navia et al., 2013). Mann et al. (2014) demonstrated that when expert handball goalkeepers implicitly accrued knowledge of an opponent penalty taker's action tendencies over a training period, they biased their subsequent judgements according to those tendencies resulting in a congruency effect – i.e. accuracy was increased for actions congruent with the prior tendencies and decreased for incongruent ones. Explicit accrual of contextual priors is similarly effective as shown by Gray (2015) who provided expert baseball batters with explicit information about a pitcher's action tendencies. Simulated batting performance improved immediately, and after a training period. However, when the batters faced a new simulated pitcher, with different action tendencies, the explicit provision of contextual priors adversely affected performance.

Contextual priors can also be *dynamic* and emerge as the action unfolds, such as opponent positioning (Huesmann & Loffing, 2019; Loffing et al., 2016; Loffing & Hagemann, 2014b; Murphy et al., 2016; 2018; 2019). Loffing and Hagemann (2014b) used a video-based experiment in which the court positions of a tennis opponent were systematically manipulated but stroke kinematics remained constant. The footage was temporally occluded at three different time points. Skilled tennis players' anticipatory judgements were more influenced by the opponent's court position than less-skilled players, due to their ability to detect and use this information. Moreover, the skilled players became more reliant on the priors under early temporal occlusion conditions in which the reliability of the kinematic information was low. Taken together, the extent to which stable and dynamic contextual priors affect performance is contingent on their congruency, and temporal integration, with evolving kinematic information.

Integrating contextual priors with kinematic information

Runswick et al. (2018a; 2018b; 2018c) examined the processing priorities of expert and novice cricket batters as they predicted the bounce point of a bowler's forthcoming deliveries, with and without contextual priors. When facing six consecutive deliveries from the same bowler, which revealed action tendencies, and after receipt of prior information pertaining to the game score and field setting (i.e. positions of opponents), both expert and novice batters' response accuracy improved, compared to when facing six successive deliveries from six different bowlers in the absence of prior information about the game situation. Verbal report data revealed that when contextual priors were provided, the expert batters, more so than novices, verbalised a higher number of statements relating to prior information about the bowlers' action tendencies, the state of the game, and the field setting, whereas fewer statements referred to the bowlers' kinematic information (Runswick et al., 2018a). Runswick et al. (2018c) demonstrated that this prioritisation of contextual priors, over and above the use of kinematic cues, resulted in a congruency effect that was greater for experts than novices. Using the same task, Runswick et al.

(2018b) combined temporal occlusion with a retrospective information score rating in order to explore the temporal interaction of contextual priors and evolving kinematic information. The ratings revealed that the batters' reliance upon contextual priors was dominant during the early stages of the bowler's run-up, whereas information relating to the bowler's kinematics and ball flight became the dominant sources of information nearer to the point of ball release. The reliance on contextual priors (during the early stages of run-up) and pertinent kinematic information (around ball release) was more pronounced in expert compared with novice batters.

Gray and Cañal-Bruland (2018) employed the same task as Gray (2015) to examine the effect of contextual priors on anticipation in baseball batting. However, in addition to priming the batters with explicit information about the pitcher's action tendencies, they altered the reliability of these action tendencies (e.g. the chance that the pitcher would throw a fastball was either 50%, 65%, or 80%) and the reliability of pertinent kinematic information (the ball was occluded 50, 100, and 150 ms after the pitcher had released the ball). The batters performed best in the condition with high-reliability contextual priors (e.g. fastball = 80% chance) and high-reliability kinematic information (i.e. ball occlusion after 150 ms). In line with the findings of Runswick et al. (2018b), the batters used the priors to make early adaptations to their swing, whereas pitcher's kinematics informed late swing modifications. Furthermore, the impact of contextual priors on batting performance increased as the reliability of kinematic information decreased (see also, Gredin et al., 2020a).

The research reviewed so far highlights that, in addition to kinematic information, athletes use contextual priors to inform their anticipatory judgements. These studies indicate that awareness of priors, be they dynamic (Loffing & Hagemann, 2014b; Murphy et al., 2016) or stable (Gray, 2015; Mann et al., 2014), biases athletes' anticipatory judgements toward the most likely outcome. The effects of contextual priors, on both anticipation skill (Loffing et al., 2015) and processing priorities (Runswick et al., 2018a; 2018b), seems to be more pronounced in expert than novice athletes. It appears that an athlete's dependency upon contextual priors is contingent on the reliability of the priors (Gray & Cañal-Bruland, 2018), as well as the reliability of evolving kinematic information (Gray & Cañal-Bruland, 2018; Loffing & Hagemann, 2014b; Runswick et al., 2018b). This notion is supported by the congruency effects found in the absence of reliable kinematic information (Loffing et al., 2015; Loffing & Hagemann, 2014b; Mann et al., 2014; Runswick et al., 2018a; 2018b; 2018c). Athletes seek to optimize anticipation by integrating kinematic information and contextual priors, with their respective contributions weighted by their reliability.

Recently, researchers have utilised qualitative approaches, such as interviews with expert athletes, to provide insight into the complex interplay between various sources of information when making decisions (Levi & Jackson, 2018; Schläppi-Lienhard & Hossner, 2015; Vernon et al., 2018). Vernon et al. (2018) interviewed eight expert tennis players about their use of kinematic information and contextual priors when returning a serve. The study revealed several information sources and, on the basis of this, the authors developed a temporal model that built on that of Müller and Abernethy (2012). In line with the previous discussions, the new model suggests that stable contextual priors may be acquired hours or even days before the competition (e.g. opponent action tendencies), and are subsequently updated with dynamic contextual priors (e.g. opponent court position) and kinematic information (e.g. ball toss) as the serving

action evolves. The authors suggested that anticipatory judgements become predominantly influenced by kinematic sources as the action unfolds. While Vernon et al. (2018) model is a useful extension of Müller and Abernethy's (2012), it does not explain *how* the various sources of information are integrated together to produce fast and accurate anticipatory judgments.

Current models for explaining the integration of contextual priors and kinematic information

Cognitive approaches to anticipation and decision making predict that decisions are made through the integration of separate processes that build on one another in a sequential manner (Raab et al., 2019). Rather than the environment shaping the performer's actions in an interdependent and embodied manner (the ecological approach; Araújo et al., 2019), the cognitive approach assumes that environmental information must be encoded for internal mechanisms to transform it in to a meaningful representation (Williams & Abernethy, 2012). This allows for interpretation of the environment and subsequent implementation of an action. A number of models have emerged from the cognitive approach that have been applied to anticipation in sport. The computational model (Busemeyer & Johnson, 2004) suggests that individuals process the sources of information available in a sequential manner until a threshold of preference for one option is met (Johnson, 2006). The Long-Term Working Memory (LTWM) theory (Ericsson & Kintsch, 1995), a computational model, suggests that experts are able to make faster and more accurate decisions than novices because they have developed retrieval structures through sport-specific practice, which promote rapid encoding and retrieval of information, bypassing the limitations of short-term and long-term memory (Ericsson & Lehmann, 1996; Williams & Ericsson, 2005).

In contrast, the simple heuristics model predicts that fast decisions are made based on a sequence of search, stopping, and decision rules (Raab, 2012). A heuristic is a strategy that, compared to more complex methods, does not integrate all sources of available information and instead deliberately ignores cues to make decisions more quickly. Some examples of simple heuristics include the *take-the-first heuristic* (e.g. Raab & Johnson, 2007), in which expert performers are predicted to generate two or three options and then choose the first option generated, and *take-the-best heuristic* (e.g. Bröder, 2000), in which an option is generated according to the most discriminating cue. This simple 'less-is-more' model has been shown to outperform more complex 'full-information' models (Gigerenzer & Gaissmaier, 2011; Johnson & Raab, 2003; Raab & Gigerenzer, 2005).

Recently, a Bayesian framework has been discussed in the sport anticipation literature (e.g. Gredin et al., 2018; Helm et al., 2020; Loffing & Hagemann, 2014b). Bayesian theory contradicts the heuristics model, as it advocates that additional information processing is always beneficial for decisions, if it is correctly combined with appropriate prior knowledge. Researchers have suggested that a simple heuristics model may be equivalent to a Bayesian model in the presence of extreme priors (Parpart et al., 2018). For example, where the reliability of priors is 100%, new emerging environmental information would not be required, as in a simple heuristics approach. However, in a scenario where the priors are say 75% reliable, integration of down-weighted environmental information with the priors, as per Bayesian theory, is preferable to entirely ignoring it. While other cognitive approaches, such as simple heuristics, have been discussed at length in the

sport anticipation literature (e.g. Raab, 2012; Raab et al., 2019), Bayesian theory has yet to be fully explored. Given the unpredictable and ever-changing nature of sport, it seems appropriate to examine the applicability of a Bayesian integration framework for anticipation. In the following section, we discuss key components of Bayesian theory, including research from non-sport domains, and then discuss the sport anticipation research that has drawn on this framework.

Toward a Bayesian integration framework

At any given time, the world only provides us with partial and noisy cues regarding its actual state (Brunswik, 1952). According to Brunswik (1955), the actual state of the world should be seen as a *distal variable* that cannot be directly perceived, but has to be assessed through a 'lens' of *proximal variables* that provide probabilistic information about the distal variable. A fundamental question for human perception and cognition is, 'how do people make inductive judgements that inform their subsequent behaviours from such incomplete information?'. Scientists have tried to answer this question by suggesting that people use Bayesian reliability-based strategies to combine available pieces of ambiguous information, in order to reduce the uncertainty of their judgements as much as possible. Bayesian theory suggests that incoming environmental cues, termed *likelihoods*, are continuously combined with domain-specific knowledge, termed *priors*, to produce a *joint estimate* at a single point in time (Körding, 2007). Bayesian models for probabilistic inference assume that people base their judgements on probabilistic *if-then* relationships between known informational variables (or 'proximal variables' in Brunswikian terms) and unknown to-be-anticipated variables (or 'distal variables' in Brunswikian terms). That is, *if 'X'* (a known informational variable) occurs, *then* there is a certain probability that 'Y' (an unknown to-be-anticipated variable) will occur. This process suggests that, if one informational variable is associated with greater reliability (i.e. lower uncertainty) than another, then the individual's joint estimate should be biased toward the more reliable informational variable (Knill & Pouget, 2004). Each joint estimate results in updated expectations, termed *posterior probability*, which act as a new prior to be combined with emerging environmental information (Körding & Wolpert, 2006). This continuous updating of expectations allows for efficient decisions to be made in dynamic and ever-changing environments.

Combining environmental cues

According to Bayesian theory, each informational variable in our environment has an associated probability distribution that characterises the extent to which it predicts the occurrence of a to-be-anticipated variable. These probability distributions may arise from multiple sources and sensory modalities. In such instances, the observer combines environmental information according to their comparative reliability, resulting in a joint probability distribution that ultimately forms the basis for their judgement (Vilares & Körding, 2011). For example, consider a doctor who is tasked with diagnosing a patient's condition (the to-be-anticipated variable; e.g. heart attack, viral illness) based on specific presenting symptoms (the informational variables; e.g. arrhythmia, pain/discomfort). Each symptom has associated probability distributions, for a range of potential underlying conditions. When

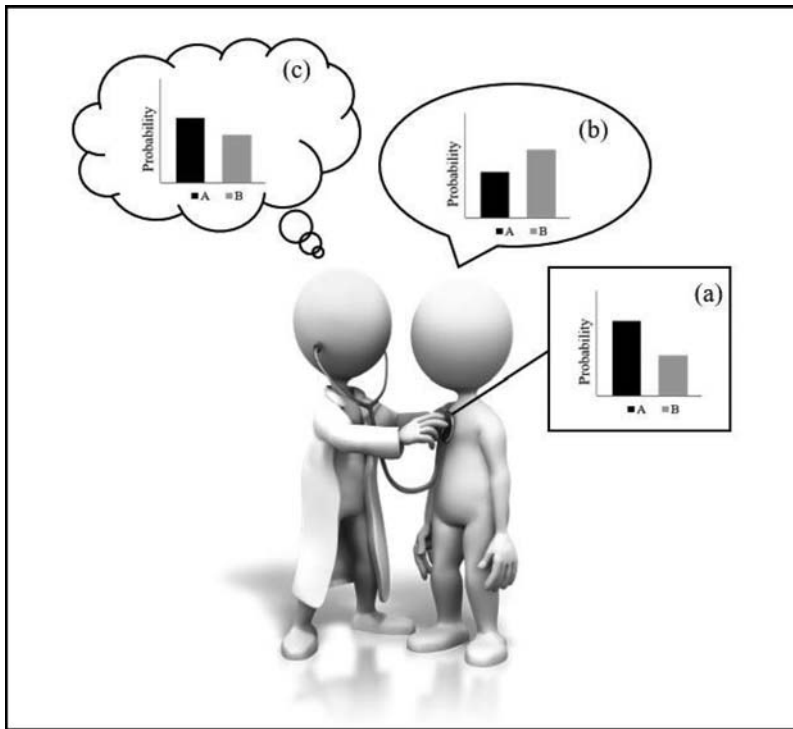


Figure 1. Doctor using reliability-based strategies to combine environmental cues. The doctor assesses the likelihood that a patient is suffering from Disease A or Disease B by weighing objectively measurable symptoms (a) against self-reported symptoms (b). The doctor assigns higher reliability to the former symptoms which is reflected in her joint estimate (c) of the patient's clinical state.

taking these symptoms into account, the doctor may consider objectively measurable symptoms (e.g. arrhythmia) to be more reliable than the patient's self-reported symptoms (e.g. pain). While both symptoms are considered when making their judgement, the perceived lower reliability of the latter would be reflected in the joint probability distribution and, as such, in the doctor's estimate of the patient's clinical state (see Figure 1).

This weighted reliance upon environmental sources of information has been demonstrated in the combination of visual and auditory cues in order to localise events in space (Alais & Burr, 2004; Battaglia et al., 2003), or visual and haptic cues in order to estimate the size of objects (Ernst & Banks, 2002). People also combine information sources via the same modality (e.g. visual information) in a reliability-based manner. For example, when estimating object shapes (Jacobs & Fine, 1999) or surface slants (Knill & Saunders, 2003), people integrate texture and motion (Jacobs & Fine, 1999) or texture and binocular disparity (Knill & Saunders, 2003), and their ultimate estimates are determined by the reliability of these sources.

Integrating priors with environmental cues

People do not typically develop their inductive judgements about the world using sensory information alone; prior knowledge and beliefs also impact their judgements.

In Bayesian terms, these priors constitute the probability distribution regarding the state of the to-be-anticipated variable, prior to the point at which the reliability of current sensory information is taken into account (Vilares & Körding, 2011). These priors effectively summarise task-relevant information that an individual has accrued over time (Berniker et al., 2010) and, as such, they contribute to expertise in a given domain. In dynamic tasks, such as sport, the joint estimate formed from the integration of environmental cues acts as a prior in the next computational instance and is combined with new environmental information (Körding & Wolpert, 2004). Priors can also be introduced before any relevant environmental information is present in the form of domain-specific knowledge, referred to in this paper as contextual priors. For example, task-relevant prior information has been introduced into experimental designs (Serriès & Seitz, 2013). In simple arm-reaching (Brouwer & Knill, 2009), pointing (Tassinari et al., 2006), and event-timing (Miyazaki et al., 2005) tasks, researchers have demonstrated that people integrate priors that are related to the distribution of the target location, and evolving visual information in a manner described by Bayesian models for probabilistic inference. That is, reliance on priors and visual information is contingent upon the comparative reliability of the information at hand; dependency on priors increases as the reliability of visual information sources decreases, and vice versa. In the case of the doctor making a diagnosis described earlier (Figure 1), they may study their patient's prior medical records before meeting them. The reliability of this prior information would be weighed against the reliability of the presenting symptoms in order to optimise diagnosis accuracy (see Figure 2).

In keeping with research using simple and generic sensorimotor tasks (e.g. Brouwer & Knill, 2009; Miyazaki et al., 2005; Tassinari et al., 2006), it has been demonstrated that, in

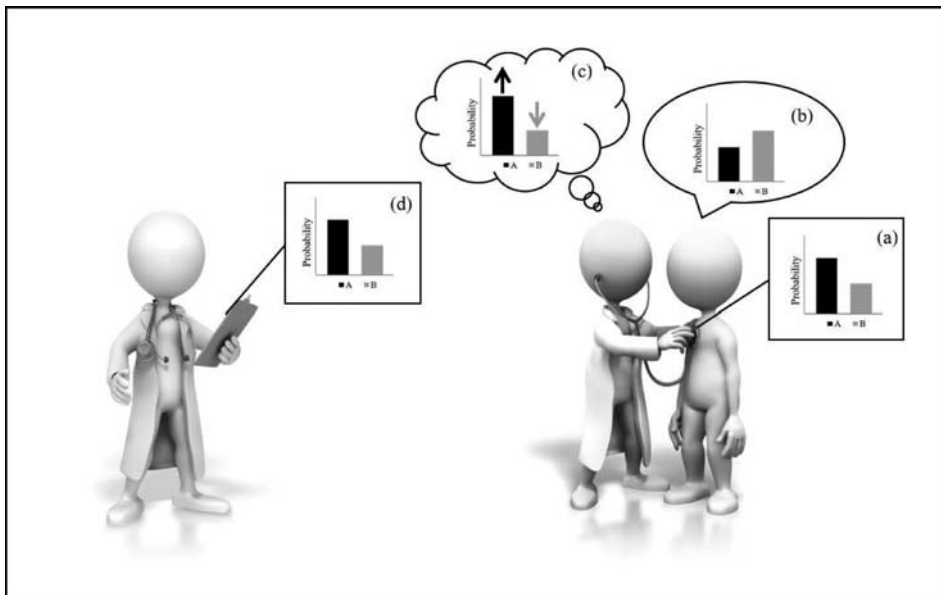


Figure 2. Doctor integrating priors with environmental cues. The doctor integrates the patient's medical records (d) with measurable symptoms (a) and self-reported symptoms (b) which modulates the doctor's joint estimate (c) of the likelihoods for Diseases A and B.

applied settings, people integrate contextual priors and visual information in a reliability-based manner. For example, in forensics, Dror et al. (2005) reported that, when people were primed with additional contextual priors (e.g. background stories and photos from the crime scene), they were more likely to make 'match' judgements between fingerprints. However, the likelihood of doing so was only increased for ambiguous (i.e. low reliability), and not for clear (i.e. high reliability), fingerprints. Furthermore, it has been suggested that the addition of contextual priors biases the individual's allocation of attention by inducing a top-down, context-driven, selection of visual information (Torralba, 2003). This issue has been demonstrated in law enforcement, where contextual priors biased police officers' allocation of visual attention toward context-relevant visual information, as well as their responses on a judgement task (Eberhardt et al., 2004).

The previous research, and the examples provided, in this section illustrate how priors are integrated with environmental cues according to Bayesian theory. However, they don't adequately reflect the processes occurring during anticipation in sport. Sport provides a unique environment where sensory inputs are continuously and rapidly changing. The next section discusses recent research from the sport anticipation literature that has assessed the applicability of Bayesian theory as a framework.

Bayesian theory as a framework for anticipation in sport

The idea of using Bayesian theory as a framework for anticipation in sport is not a new one. Newell (1974) referred to Bayesian rule formation when discussing baseball batting and the problem of performing optimally under high spatiotemporal constraints. However, this notion did not gain traction in the sport anticipation literature until recently when a number of experimental papers provided compelling arguments for the applicability of Bayesian integration theory as a framework to explain anticipation in sport (e.g. Gredin et al., 2018; 2019; 2020a; 2020b; Helm et al., 2020; Loffing et al., 2016; Loffing & Hagemann, 2014b).

When examining the impact of court positioning on anticipation in tennis, Loffing and colleagues (2014b; 2016) speculated that the findings could be explained using Bayesian theory. Court positioning had a greater influence on anticipatory judgements in the early stages of the opponent's action when there was greater uncertainty as the kinematic information was less reliable. In the later stages of the action (i.e. at racket-ball-contact) the kinematic information was more reliable and so the skilled tennis players assigned more weight to this cue, compared to the dynamic contextual prior, when making their final judgement. The authors suggested that 'tennis players may follow a Bayesian strategy by continuously updating the probabilities regarding their opponent's stroke outcome based on weighted computations of incoming sensory information and domain-specific knowledge of situational probabilities' (Loffing et al., 2016, p. 201).

Gredin et al. (2018) used a 2-versus-2 video-based soccer anticipation task, to design a study that required expert and novice players to integrate dynamic contextual priors, in the form of opponent positioning, in order to utilise stable contextual priors, which related to opponent action tendencies. In each trial, there was one attacking player in possession of the ball, a second attacker off the ball and one defender marking the second attacker. Halfway through each trial, the second attacker made a direction change towards either the left or the right. At the end of the trial the attacker in possession

would either pass the ball to his teammate or dribble the ball in the opposite direction. The participants were required to anticipate the direction of the final action of the attacker, either left or right. Importantly, the stable contextual priors were the action tendencies of the attacker in possession (i.e. dribble 67%; pass 33%), rather than the likelihood that the end outcome was left or right (cf. Broadbent et al., 2018). The final position of the second attacker was therefore critical for interpretation of the stable priors and subsequent anticipation of the final action (i.e. if the attacker off the ball was on the left side, 67% of the attacker in possession's final actions were to the right, and vice versa). In line with Bayesian theory, the findings revealed that explicit provision of opponent action tendencies altered how expert players, but not the novices, allocated their overt visual attention toward the context-relevant position of the attacker off the ball (Eberhardt et al., 2004; Torralba, 2003). In other words, the stable contextual priors altered the expert players' expectations – and consequently, their perception of the unfolding information (see De Lange et al., 2018, for a review of this phenomenon). When the kinematic information was ambiguous during the early stages of the trial, the stable contextual priors had greater impact on skilled players' perception by increasing the relevance of the second attacker's position. This, in turn, biased the expert players towards the most likely action, given the opponent's action tendencies, which improved performance when the final action was congruent with those tendencies (see also Navia et al., 2013). Interestingly, on incongruent trials, the explicit priors had a negative impact on anticipation in novices, whereas experts maintained their performance – a finding that contradicts previous research showing greater congruency effects for experts than novices (e.g. Loffing et al., 2015; Mann et al., 2014; Runswick et al., 2018b). Gredin et al. (2018) argued that the use of the temporal occlusion paradigm in previous research restricted the experts' use of reliable kinematic cues in the final stages of the action. In the study by Gredin et al. (2018) the occlusion point was after the final action of the opponent and therefore, in line with Bayesian theory, the experts could update prior expectations by integrating more reliable kinematic information in the final stages (Körding, 2007). [Figure 3](#) depicts the findings from the study by Gredin et al. (2018) in line with Bayesian theory.

Helm et al. (2020) provided a more direct assessment of the applicability of a Bayesian framework for anticipation in sport in contrast to a heuristics-based framework. Using a handball penalty anticipation task, they tested the assumptions of a simple heuristics model (i.e. no integration model), an equal weighting model, and a Bayesian integration model (i.e. reliability-based weighting model). The authors systematically manipulated the reliability of both the contextual priors, related to the action preferences of the penalty taker, and the kinematic information emanating from this opponent. The kinematic ambiguity of human-like avatars of handball throwers was altered by varying the degree to which the throw was disguised or not. The authors showed 49 different handball penalty throws across seven levels of kinematic ambiguity: (1) exaggerated genuine throws; (2) genuine throws; (3) morphs with 25% disguised kinematics; (4) morphs with 50% disguised kinematics; (5) morphs with 75% disguised kinematics; (6) disguised throws; (7) exaggerated disguised throws. In three experimental conditions, novice participants were explicitly informed about the opponent's action preference to disguise their throw: 25% probability of disguised throws; 50% probability of disguised throws; and 75% probability of disguised throws. The actual probability of a disguised throw was 50%,

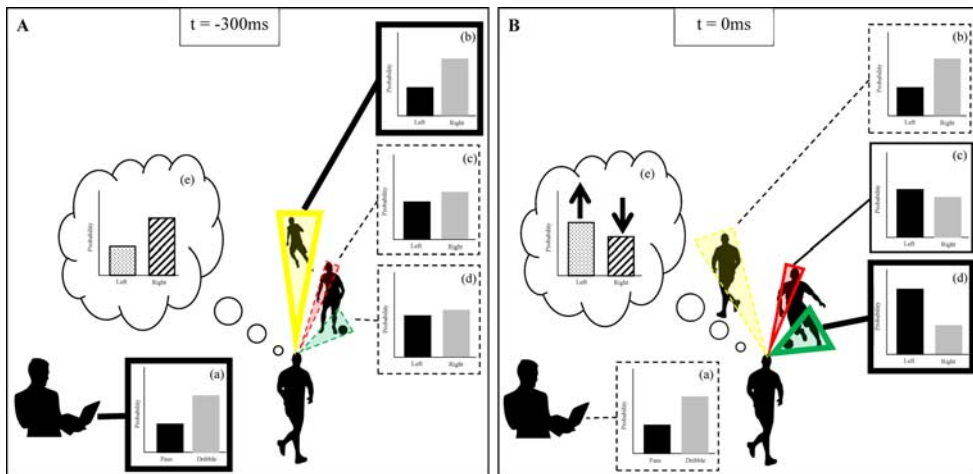


Figure 3. An expert soccer player integrating stable and dynamic contextual priors with kinematic cues over time to produce an anticipatory judgement. **(A)** The action tendencies of the opponent are evaluated prior to the action [stable contextual priors] (a) but can only be utilised effectively by monitoring the evolving position of the player off the ball [dynamic contextual prior] (b). These contextual priors are assigned greater weighting in the early stages of the action (represented by a thick border line) when kinematic cues, such as the positions of the head (c) and lower leg (d), are ambiguous and less reliable (represented by a dashed border line) resulting in biased expectations in line with the opponent's action tendencies (e). **(B)** The player assesses the likelihood that the opponent will go 'left' or 'right' by continuously weighting the various kinematic cues (c; d), and updating their expectations based on this. The player assigns higher reliability to the lower leg cues due to domain-specific knowledge, which is reflected in their joint estimate that is used as a prior in the next computational state. As the action unfolds, the player assigns greater weighting to the more reliable kinematic information than to the contextual priors (a; b), and updates their expectations accordingly. To produce a final anticipatory judgement (e), the player integrates the evolving kinematic cues with the contextual priors, based on their weighted reliabilities.

so this condition was used as the control. The results revealed that the interpretation of kinematic information was biased by the contextual priors. Participants were more likely to classify ambiguous movements as genuine when they were explicitly informed that the opponent was less likely to produce disguised throws (25% vs 50%) and more likely to classify ambiguous throws as being disguised when they expected the opponent to produce disguised throws (75% vs 50%). Moreover, the greater the degree of ambiguity in the kinematic information the more weight placed on the contextual priors by the participants when forming an integrated anticipatory response. In essence, individuals rely more strongly on contextual priors when the reliability of the kinematic information becomes less certain. The findings supported the use of the Bayesian integration model, over simple heuristics and equal weighting models. Performance was not optimised by discarding information in a manner consistent with a simple heuristics model, or by processing all information equally as proposed by the equal weighting model. Instead, participants were able to accurately assess the reliability of the contextual priors and the kinematic information, and continually update the assigned weightings during unfolding actions, in order to flexibly integrate information sources and yield the outcome with the highest likelihood of success.

The previous studies highlight that a Bayesian framework could add value when explaining and predicting anticipation in sport. According to Bayesian theory, the integration of contextual priors and kinematic information may be moderated by other factors, in addition to informational reliability. In the next section, we discuss the potential cognitive load associated with this integration process and how the impact of contextual priors may be modulated by task load and judgement utility.

Factors moderating the integration of contextual priors and kinematic information

Several factors are suggested to moderate the integration of contextual priors and kinematic information. We previously introduced some of these factors, such as the skill level of the athlete. Bayesian theory predicts that experience of any given domain leads to the development of specific knowledge that enables sophisticated understanding of the reliability of information sources and the associated situational probabilities (Serìès & Seitz, 2013; Yarrow et al., 2009). As we discussed earlier, it appears that, as a result of domain-specific practice, experts are better able to identify important sources of information, assess their reliability, assign situational probabilities, and flexibly integrate the weighted information to produce a response with the highest likelihood of success (e.g. Gray & Cañal-Bruland, 2018). Novices are unable to fully complete any of these steps due to a dearth of domain-specific knowledge. While skill level has been discussed throughout this paper, two important moderating factors that have not been discussed so far are *task load* and *judgement utility*.

Task load

It is believed that the inference and application of probabilistic *if-then* rules, as proposed by Bayesian theory, involves semantic memory retrieval processes (De Neys et al., 2002) and that increased integration of a priori probabilistic rules may lead to increases in cognitive load (Waldmann & Hagmayer, 2001). For example, during learning of a videogame task requiring fine motor control, Green and Flowers (2003) showed that the explicit provision of prior rules pertaining to the relationship between task features (i.e. *if 'X' occurs, then there is a specific probability that 'Y' will occur*) hampered performance during the early stages of learning, compared to when these rules were not explicitly provided. The authors proposed that the effort expended in trying to remember and apply prior probabilistic rules may detract from an individual's cognitive resources and result in inferior performance, relative to when such rules are not explicitly provided. The assumption that explicit priors may elicit increases in cognitive load has also been proposed in the domains of educational psychology (Reber, 1989), motor learning (Masters, 1992) and sport (Jackson & Farrow, 2005).

As noted in the previous section, the integration of contextual priors may affect the processing strategies that people employ in order to acquire unfolding information during task performance; notably, the use of top-down, versus bottom-up, attentional processes. Top-down processing refers to strategic allocation of attention and acquisition of information that is driven by the individual's prior knowledge and beliefs. Bottom-up processing, on the other hand, refers to automatic, externally driven, capture of attention

and information acquisition, without top-down mediation (Corbetta & Shulman, 2002). Top-down allocation of visual attention is mediated by the central executive and is therefore deemed to impose greater processing demands than bottom-up, or stimulus-driven, attentional processes (Kaplan & Berman, 2010). Thus, it can be assumed that the integration of contextual priors with evolving kinematic information during anticipation may increase cognitive load (i.e. the load imposed on working memory by cognitive processes; Antonenko et al., 2010).

Consequently, it is reasonable to suggest that contextual priors should be less effective, in terms of anticipation performance and associated processing strategies, under conditions in which task load (i.e. the complexity of elements inherent in the task; Sweller, 2010) exceeds the limited resources of working memory (see Paas et al., 2003). Runswick et al. (2018a) tested these assumptions using the Rating Scale for Mental Effort (RSME; Zijlstra, 1993) to provide an assessment of the cognitive load that cricket batters perceived they had invested in the anticipation task. In contrast to their predictions, contextual priors pertaining to the cricket bowler's action tendencies, game state, and field setting did not alter the batters' perceived cognitive load. These findings align with those reported in studies by Broadbent et al. (2018) and Runswick et al. (2017) in which RSME was used to assess the processing demands of using contextual priors during anticipation tasks in soccer and cricket, respectively. Furthermore, Runswick et al. (2018a) implemented a backward-counting task in their design, in order to test the impact of contextual priors under conditions of increased task load. In contrast to predictions, the beneficial effect of priors was greatest under conditions of high task load, for both expert and novice groups. Retrospective verbal reports of thoughts revealed that increased task load affected the batters merely at a behavioural level, without changing their processing priorities during task performance.

These findings contradict the assumptions that contextual priors would elicit increased cognitive load, and that their impact on performance and processing strategies would decline under more cognitively demanding performance conditions. However, the absence of effects may have been because participants were able to inform their judgments from the stable priors alone, without having to integrate them with dynamic contextual priors. It is possible that the lack of interdependency between contextual priors reduced the cognitive resources required to use the contextual priors effectively. In an attempt to examine this proposal, Gredin et al. (2020b) utilised the same task and study design as Gredin et al. (2018), which required participants to consider dynamic contextual priors, in the form of opponent positioning, in order to use the stable priors effectively, but with the addition of a secondary n-back task. For the secondary task, following randomly selected trials, participants had to indicate the direction of the final action two trials previous. As with previous research, and in line with the Bayesian reliability-based strategies, the provision of contextual priors enhanced the performance of the expert players on congruent trials while no performance effect was found on incongruent trials. However, the performance improvement on congruent trials was not found when the secondary task was included. In contrast to the studies by Runswick et al. (2018a) and Broadbent et al. (2018), the increased task load suppressed the performance-enhancing effects of contextual priors as participants had to consider dynamic priors in order to use the stable contextual priors effectively. This interplay between different sources of contextual priors, and kinematic information, appears to be a more demanding process and therefore when a

cognitively demanding secondary task was introduced participants were less effective in their use of priors. It would be interesting to compare the impact of increased task load on the use of stable and dynamic contextual priors with varying levels of interdependency. Moreover, the load associated with a task can be increased through other moderating factors, such as anxiety (e.g. Broadbent et al., 2018) and fatigue (e.g. Alder et al., 2019). Future research should investigate how factors such as these impact the integration of contextual priors and kinematic information (e.g. Cocks et al., 2015).

Gredin et al. (2020b) combined continuous electroencephalography (EEG) and self-report measures to assess the cognitive load associated with soccer players' processing of contextual priors during the anticipation task. The EEG data suggested that explicitly provided contextual priors increased experts' cognitive load, perhaps due to the recruitment of additional attentional resources (Simonet et al., 2019). In contrast, the retrospective self-report data indicated a decrease in cognitive load when priors were provided. This brings in to question the reliability and validity of retrospective self-report measures, such as the Rating Scale of Mental Effort (RSME; Zijlstra, 1993), that are commonly used in the literature as a measure of cognitive load. The reliance on stable and dynamic contextual priors may vary across different stages of task performance (Gray & Cañal-Bruland, 2018; Gredin et al., 2018; Runswick et al., 2018a), and consequently, it is possible that the fluctuating impact of contextual priors on cognitive load was overlooked when the players were asked to retrospectively report one aggregated cognitive load score for each block of trials. Alternatively, it could be that the self-report data reflected perceptions of task difficulty, rather than perceived levels of cognitive load. Participants may perceive a task as less difficult when provided with additional task-relevant information, while at the same time being under greater cognitive load (i.e. increased working memory usage, in order to process additional information), and vice versa (see Westbrook & Braver, 2015). In future, researchers should confirm these findings and develop a more valid and reliable self-report measure of cognitive load for when psychophysiological measurements are not accessible or appropriate.

Judgement utility

When anticipating the outcomes of their own and others' actions, people not only consider the reliability of prior and current sources of information to inform their judgements, but also the utility value of potential outcomes (Vilares & Körding, 2011). Typically, researchers have discriminated procedural utility from judgement utility. The former refers to the costs and rewards associated with the strategies employed in order to solve a task (e.g. the expected energetic costs of carrying out a movement; Körding & Wolpert, 2006). The latter refers to the costs and rewards associated with the consequences of one's judgements; high judgement utility is associated with high rewards when accurate and low costs when inaccurate, and vice versa. According to Bayesian theory, the weighted average of the reliability conveyed by prior and current sources of information is convolved with the utility values assigned to possible judgements; the Bayes optimal final judgement is the one that maximises the probable utility (Geisler & Diehl, 2003).

It is noteworthy that the biasing effect of judgement utility is not only due to people's desire to gain rewards or avoid costs. The comparative utility of different judgements also

influences people's estimations of the likelihood that specific outcomes will occur. Namely, people tend to overestimate the likelihood of an outcome happening, if prediction of that outcome is associated with higher judgement utility. This biasing effect of judgement utility has been demonstrated across a variety of domains and contexts (see DeKay et al., 2009; Russo & Yong, 2011). Wallsten (1981) reported that physicians who were tasked with making diagnostic judgements assigned a higher probability to a patient having a malignant tumour than a cyst, despite the higher objective probability of a cyst. Physicians overestimated the chances of a tumour due to the more severe consequences associated with a tumour, relative to a cyst. In other words, diagnosis of a tumour would be associated with greater rewards (if correct) and lower costs (if incorrect) than would diagnosing a cyst. One purported explanation for such a utility-driven estimation is that the individual infers the information at hand as more confirmative of the judgement associated with the highest utility than it should be (Russo & Yong, 2011).

The utility associated with different judgements seems to distort people's inference of the reliability conveyed by the information at hand and consequently biases their anticipatory judgement toward the option associated with comparatively higher utility. Canál-Bruland et al. (2015) analysed the movement pattern of expert baseball batters on a batting task where they faced either fastballs (a faster type of pitch) or changeups (a slower type of pitch). By analysing the batters' movement initiations, the authors proposed that the batters expected fastballs to occur more frequently than changeups. It was proposed that expert batters use this strategy as it enables them not only to handle the severe temporal constraints of facing a fastball, but also to slow down their swing if confronted with a change-up. Conversely, expecting a change-up would not allow the batter to catch up with the speed of a fastball, which would clearly impair performance. Judgement utility (e.g. higher utility of predicting a fastball than a changeup in baseball) may bias athletes' anticipatory judgements; however, the extent to which it modulates the effects of contextual priors, and processing priorities, during task performance was not explored in this study.

Gredin et al. (2019) examined the impact of judgement utility on expert soccer players' integration of stable and dynamic contextual priors with kinematic information as they anticipated an oncoming opponent's imminent actions. Utility was informed by the location on the pitch in which the action took place (i.e. right-hand edge of the penalty area). In soccer, possession of the ball in a more central position within this area (to the participant's left in the task) typically leads to more goals than possession in a wider position (i.e. to the participant's right), further from the goal. Participants were told that if they chose 'right' as the direction of the final action and it was incorrect (i.e. the opponent went left), then that would result in a goal conceded; this meant that a decision of 'left' had the greater judgement utility. In other words, correct and incorrect 'left' responses came with greater rewards (stopping a goal) and lower costs (conceding a goal), respectively, than 'right' responses. While explicit contextual priors changed players' processing priorities, and biased their anticipatory judgements, and consequently enhanced performance, these effects were suppressed under conditions of imbalanced judgement utility. Moreover, the verbal report data suggested that judgement utility also suppressed the use of kinematic information. As depicted in Figure 4, the players became less reliant on contextual priors and unfolding kinematic information, and more inclined to opt for the high utility direction (i.e. left). As suggested by Bayesian models for informational integration, expert soccer players appear to base their

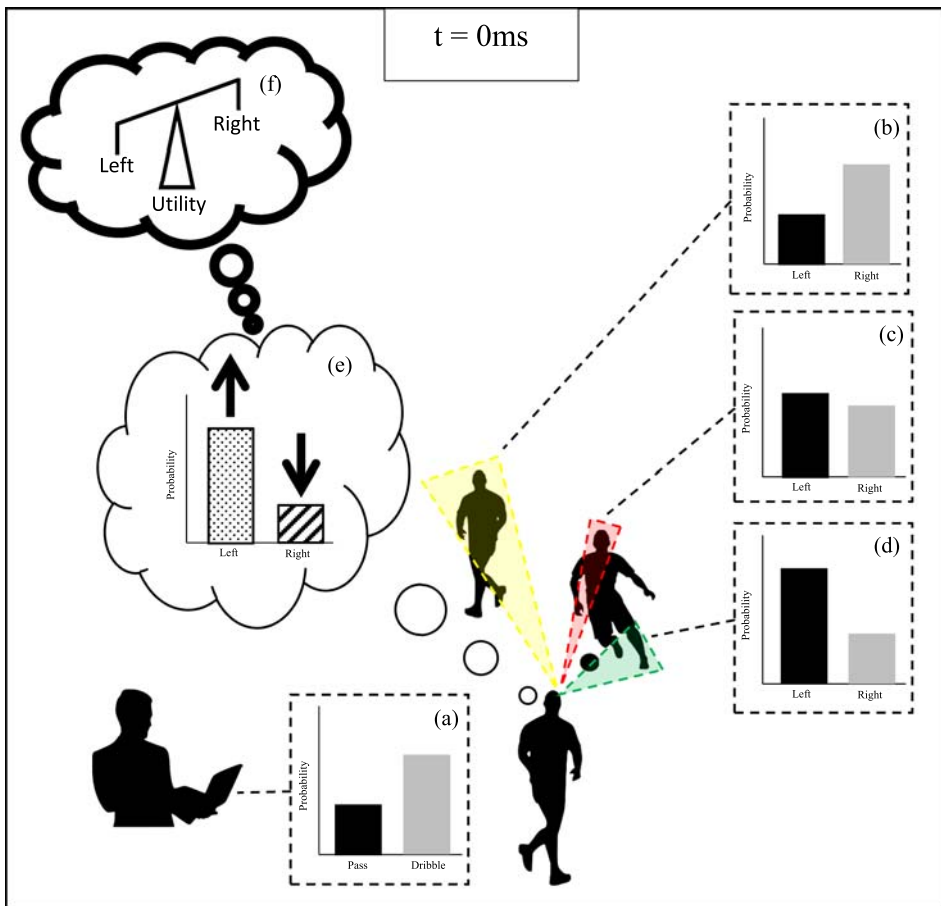


Figure 4. Expert soccer player considering the utility of anticipating left or right(f). The left option possesses greater utility due to the costs of selecting right when the ball went left (i.e. conceding a goal). The comparative utility of the two options suppresses the impact of stable (a) and dynamic (b) contextual priors, as well as evolving kinematic cues (c; d), represented by the dashed border lines, and biases the player's joint estimate toward the direction with the highest expected utility (e).

judgements not only on the reliability of available information, but also the potential costs and rewards of their actions (see Geisler & Diehl, 2003).

Conclusions

There is strong evidence that athletes integrate dynamic and stable contextual priors with evolving kinematic information to inform their anticipatory judgements (e.g. Broadbent et al., 2018; Gredin et al., 2018; Loffing et al., 2015; Mann et al., 2014; Runswick et al., 2018a; 2018b). In keeping with Bayesian theory (see Vilares & Körding, 2011), to reduce the uncertainty of the decision, athletes integrate contextual priors with kinematic information according to the comparative reliabilities of available information sources. That is, greater weight is given to sources that convey more reliable information, and vice versa

(Gray & Cañal-Bruland, 2018). Furthermore, the reliabilities assigned to contextual priors and kinematic information may change over time and appear to be modulated by the athlete's ability to infer the relevance of available information (e.g. Runswick et al., 2018a; Runswick et al., 2018b; Savelsbergh et al., 2002). It is reasonable to surmise that integration of contextual priors with kinematic information would increase cognitive load (De Neys et al., 2002; Kaplan & Berman, 2010; Waldmann & Hagmayer, 2001) and, consequently, that the impact of contextual priors would decline when the task load exceeds the limited capacity of working memory (see Paas et al., 2003). However, research in sport has shown mixed findings, with some studies supporting this hypothesis (Gredin et al., 2020b) and others not (Broadbent et al., 2018; Runswick et al., 2018a). It may be that the interdependency between stable and dynamic contextual priors and the evolving kinematic information moderate the cognitive load associated with the task – but future research is required to confirm this. Finally, the utility associated with people's judgements is likely to distort their inference of the reliability conveyed by contextual priors and visual information (Russo & Yong, 2011) and seems to bias anticipatory judgements in favour of high-utility options (Cañal-Bruland et al., 2015; Gredin et al., 2019).

It appears a Bayesian approach has several advantages over other theories proposed to explain anticipation in sport. A Bayesian framework is able to model complex behaviours, whereby information sources are continuously combined and updated efficiently, which is critical in the uncertain and ever-changing environments faced by athletes in sport. This review provides a brief overview of the current trends in the sport anticipation literature and proposes that, in future, researchers could adopt Bayesian models for probabilistic inference as an overarching framework.

Disclosure statement

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