UNIVERSITÉ DU QUÉBEC À MONTRÉAL

DÉVELOPPER UNE PRISE DE DÉCISION RÉSILIENTE LORS DES MATCHS EN WATER-POLO DE HAUT NIVEAU: DE LA RECHERCHE À L'ACTION

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LIST OF ABBREVIATIONS & ACRONYMS

ACC: Anterior cingulate cortex

AU: Arbitrary units

CHAOS: Constraints-led, Holistic Approach to Overcoming Stressors

CI: Confidence interval

CIHR: Canadian Institutes of Health Research

CLA: Constraints-led approach

DMI: Decision-making index

EF: Executive functioning

EMG: Electromyography

EMM: Estimated marginal means

FINA: World Aquatics

GPS: Global positioning system

HICE: High-intensity continuous exercise

HIIE: High-intensity interval exercise

HPA: Hypothalamus-pituitary-adrenal

ICC: Intraclass correlation coefficient

iKT: Integrated knowledge translation

IST: Integrated support team

JBI: Johanna Briggs Institute

MAP: Maximal aerobic power

MICE: Moderate-intensity continuous exercise

NASA-TLX: NASA Task Load Index

RPM: revolutions per minute

RSME: Rating Scale of Mental Effort

SD: Standard deviation

SE: Standard error

VAS: Visual analog scale

RÉSUMÉ

La prise de décision lors des matchs est un élément essentiel de la performance dans les sports collectifs comme le water-polo. Par conséquent, Water-Polo Canada a identifié l'optimisation de la prise de décision des athlètes comme une occasion d'améliorer de façon significative la performance en compétition. Ainsi, l'objectif principal de cette thèse était d'utiliser une approche basée sur des preuves scientifiques et empiriques pour développer une intervention d'entraînement visant à aider les athlètes à améliorer leur performance dans la prise de décision en match.

Le premier objectif était de créer un test spécifique au water-polo pour évaluer la prise de décision à partir de vidéos de compétitions. Il s'agissait de courtes séquences de situations de match de water-polo à partir desquelles on demandait aux athlètes d'identifier l'action offensive appropriée en utilisant leur téléphone intelligent. Nous avons étudié la validité de construit du test en comparant la précision entre des joueurs de water-polo féminins et masculins d'âge et de calibre différents (classés comme très entraînés ou élites), et sa reproductibilité en comparant les performances entre deux sessions expérimentales. Bien qu'il y ait eu des associations entre la précision et l'âge, le test n'a pas permis de distinguer les hommes très entraînés des femmes et des hommes élites, les performances n'étant différentes qu'entre les femmes très entraînées et les trois autres groupes. En outre, la précision s'est améliorée lorsque le test a été répété lors d'une deuxième séance expérimentale. Ainsi, nous avons suggéré qu'en raison de son format, le test évaluait les connaissances déclaratives du jeu plutôt que la capacité de prise de décision.

Considérant que les processus de prise de décision des joueurs de water-polo se déroulent souvent pendant un effort physique de haute intensité, le deuxième objectif était d'examiner les performances cognitives pendant l'exercice. Les athlètes de water-polo ont participé à une session expérimentale comportant une tâche cognitive générale et une autre comportant une tâche cognitive spécifique au water-polo. Simultanément à la tâche cognitive, les athlètes ont suivi un protocole d'exercice sur un ergocycle comprenant différentes conditions d'intensité. L'augmentation du temps de réaction lors de l'exercice à haute intensité par rapport à l'exercice à intensité modérée était liée à la durée de l'exercice et au type de tâche. Parmi les réponses perceptives auto-rapportées, l'affect était positivement associé à la performance sur la tâche cognitive générale, et la demande perçue était plus élevée pour la tâche générale que pour la tâche spécifique au sport. Les performances cognitives des athlètes au cours de l'exercice à haute intensité différaient des tendances observées chez les populations non sportives, et nos résultats impliquent qu'elles peuvent également être spécifiques à la tâche. Nos résultats ont souligné également la valeur d'une exploration plus approfondie de la manière dont la durée de la tâche et les perceptions subjectives des athlètes influencent les performances.

Lorsqu'il s'agit de perturber la prise de décision, la fatigue est un coupable fréquemment cité. Cependant, les conclusions de la littérature semblent varier. Le troisième objectif était donc de réaliser une revue de portée afin de présenter un portrait de la recherche existante et de décrire ce qui est connu des effets de la fatigue sur les performances perceptivo-cognitives chez les athlètes de sports à compétences ouvertes. Nous avons décrit en détails les différentes méthodes utilisées pour induire la fatigue, attester de sa

présence et évaluer les performances perceptivo-cognitives. En outre, nous avons identifié les lacunes de la recherche en ce qui concerne la participation des femmes, les méthodes pour induire la fatigue et d'évaluer les performances, souvent peu spécifiques au sport, ainsi que la mesure des performances perceptivo-cognitives *au cours de* la tâche de fatigue. La fatigue a été associée à des diminutions, à des améliorations ou à l'absence de changements dans les performances perceptivo-cognitives. Ces conclusions équivoques sur les effets de la fatigue peuvent être liées à des différences méthodologiques entre les études, mais elles ont également souligné qu'il peut être important de prendre en compte d'autres facteurs induisant un stress qui pourraient avoir un impact négatif sur les performances, indépendamment et en interaction avec la fatigue.

Sachant que les résultats dérivés des devis statiques de laboratoire peuvent être limités dans leur applicabilité pour comprendre les phénomènes sur le terrain de jeu, le quatrième objectif était d'étudier le lien entre la fatigue et la prise de décision dans le contexte de matchs lors de compétitions réelles. Toutes les décisions offensives en possession du ballon prises lors de six matches internationaux ont été jugées bonnes ou mauvaises et des analyses d'événements récurrents ont été menées pour déterminer si le risque de mauvaises décisions augmentait avec le temps. Bien qu'une augmentation globale du risque au cours d'un match ait été observée, l'ampleur de cette augmentation semblait négligeable, en particulier comparée au degré élevé de variation des profils de risque des matchs individuels. Les comparaisons entre les matches n'ont pas révélé d'augmentation du risque au fur et à mesure que le tournoi avançait. Ces résultats suggèrent que la prise de décision offensive des équipes ne diminue pas systématiquement avec la fatigue, ce qui renforce que des facteurs contextuels autres que la fatigue influencent la performance.

Le cinquième et dernier objectif était de consolider les évidences tirées de la littérature scientifiques avec les résultats et les idées issues de notre propre recherche et de les appliquer sur le terrain. Plus précisément, nous avons visé l'utilisation d'une approche intégrée d'application des connaissances, dans laquelle les athlètes et le personnel de Water-Polo Canada sont devenus des collaborateurs et non simplement des participants, afin d'intégrer des entraînements plus représentatifs. Grâce à une approche mixte comprenant des groupes de discussion ainsi que des comparaisons de la charge auto-rapportée lors des compétitions et de l'entraînement régulier, nous avons peaufiné notre compréhension des défis perçus par l'équipe. Par la suite, nous avons intégré l'expertise du personnel et les connaissances théoriques pour co-concevoir CHAOS (Constraints-led, Holistic Approach to Overcoming Stressors). Concrètement, ce processus a abouti à la création d'exercices d'entraînement originaux adaptés aux objectifs tactiques spécifiques de l'équipe, tout en conservant des éléments visant à stimuler l'adaptabilité des joueurs.

Nos activités de recherche ont été catalysées par des questions pratiques provenant du terrain, et cette thèse décrit des travaux qui - en utilisant à la fois des approches scientifiques traditionnelles et innovatrices, et en étant guidé par des connaissances émergentes – ont contribué à transformer la recherche en actions.

Mots clés: fatigue; fonctions cognitives, approche par contraintes; mobilisation de connaissances intégrées

ABSTRACT

Match-play decision making is an integral component of performance in team ball sports, such as water polo. Accordingly, optimizing athletes' decision making was identified by Water Polo Canada as an opportunity to make meaningful enhancements to competitive performance. Thus, the overarching goal of this thesis was to use an evidence-based approach to develop a training intervention aimed at helping athletes enhance their match-play decision-making performance.

The first objective was to create a water polo-specific video-based test to assess decision making. It consisted of clips of water polo game situations that required participants to use their smartphone to identify the appropriate offensive action. We investigated the construct validity of the test by comparing accuracy between female and male water polo players of varying age and calibre (classified as highly-trained or elite), and its test-retest reliability by comparing performances between two experimental sessions. Although there were associations between accuracy and age, the test was not able to distinguish between the highly-trained males and the elite females and males, with performance only differing between the highly-trained females and the other three groups. Furthermore, there was an improvement in accuracy when the test was repeated. We suggested that, due to the test's format, it evaluated declarative game knowledge, rather than decision-making skill.

Considering that water polo players' decision-making processes often occur during simultaneous high-intensity physical effort, the second objective was to examine cognitive performance during exercise. Water polo players completed one experimental session that involved a domain-general task and another that involved a domain-specific task. Simultaneous to the cognitive task, they completed an exercise protocol on a cycle ergometer that consisted of different exercise conditions. Increases in reaction time at high- compared to moderate- intensity exercise were related to exercise duration and task type. Among the self-reported perceptual responses, affect was positively associated with domain-general cognitive performance, and perceived demand was higher for the domain-general compared to the domain-specific task. Athletes' cognitive performance during high-intensity exercise differed from patterns exhibited by non-athlete populations in previous research, and our findings imply it may also be task-specific. Our results also pointed to the value of further exploring of how task duration and participant self-perceptions factor into performance.

When it comes to disruptions to decision-making, fatigue is a frequently cited culprit. However, there appear to be varied conclusions in the literature. The third objective was therefore to conduct a scoping review to paint a portrait of the existing research and describe what is known about the effects of fatigue on perceptual-cognitive performance among open-skill sports athletes. We outlined in detail the different methods used to induce fatigue, attest to its presence, and assess perceptual-cognitive performance. Additionally, we identified research gaps related to female participation, sport-specific methods of inducing fatigue and assessing performance, and the measurement of perceptual-cognitive performance *during* the fatiguing task. Fatigue was associated with declines, improvements, as well as no changes in perceptual-cognitive performances. These equivocal conclusions about the effects of fatigue may be related to methodological differences between studies, but also highlight that it may be important to consider other stressors, that could negatively impact performance independently and in interaction with fatigue.

With the awareness that results derived from static laboratory designs may be limited in their applicability for understanding phenomena on the playing field, the fourth objective was to investigate the link between fatigue and decision-making performance in the context of real competition matches. All offensive on-ball decisions from six international matches were judged as good or poor and recurrent events analyses were conducted to examine if the hazard for poor decisions increased over time. Although there appeared to be an overall increase in hazard over the course of a match, the scale of the increase appeared negligible – particularly when compared to the high degree of variation in the individual hazard profiles of the games. Comparisons between the matches did not demonstrate increased hazard as the tournament progressed. These results suggest that team offensive decision-making performance does not categorically decrease with fatigue, further reinforcing that there are contextual factors other than fatigue that influence performance.

The fifth and last objective was to consolidate evidence from the literature with findings and insight originating from our own research and apply this to the field. Specifically, we aimed to use an integrated knowledge translation approach, whereby Water Polo Canada athletes and staff became collaborators and not just participants, to integrate more representative training. By using mixed methods in this co-creation process, which included focus groups as well as comparisons of self-reported load at competition and regular practice, we refined our understanding of the team's perceived challenges. Subsequently, we integrated staff expertise with theoretical knowledge to co-design CHAOS (a Constraints-led, Holistic Approach to Overcoming Stressors). Concretely, this process resulted in the creation of original training drills that were tailored to team-specific tactical objectives, while retaining elements to challenge players' adaptability.

Our research activities were catalyzed by practical questions from the field, and this thesis describes work that – using both traditional and novel scientific approaches, and guided by emergent knowledge – helped transform research to action.

Keywords: fatigue; cognitive functions; constraints-led approach; integrated knowledge translation

INTRODUCTION

What makes an athlete great? They are often admired and celebrated for their speed, strength, endurance, form, technical repertoire. We can measure how fast they run, how much they lift, how long they last; describe the cleanness of their lines; count the number of flips. These distinguishing qualities are quantifiable, tangible, and in some ways relatable – we know how fast *we* can run, how many flips we *can't* do. But for many athletes, and in particular those who practice open-skill sports, there is another crucial attribute for their success on the field of play: their decision-making skill. It is a skill that is less concrete, challenging to capture and compare, and for which there has yet to be a consensus about its mechanisms and processes. Despite the undeniable importance of decision-making skill for sport performance, a multitude of questions remain unanswered. How do you measure it? How is performance affected by factors like simultaneous physical effort, or fatigue? And perhaps the most important question for coaches and athletes: how do you foster resilient decision making? These were some of the questions that came to the forefront when, several years ago, Water Polo Canada staff identified decreases in athletes' match-play decision-making quality that they hypothesized were linked to fatigue. This thesis outlines an evidence-based, stepwise approach, in which we transitioned from the laboratory to the field, to ultimately offer Water Polo Canada practically-relevant strategies for enhancing decision-making performance. In parallel, our work addressed important gaps in the scientific literature, resulting in five academic papers, including three published articles and two manuscripts under review (at the time of submission).

CHAPTER 1

LITERATURE REVIEW

1.1 Water polo

Water polo is as team ball sport played between two teams, each with six field players and one goalkeeper. Played on a field measuring 25 m (women) or 30 m (men) long, each match consists of four quarters of eight minutes with a break of just three minutes at halftime and two minutes between the other quarters. Teams have a 30-second shot clock to score in their opponent's goal, but can retain possession for 20 seconds after rebounds, corner throws, or earning a power play. It is a high-intensity strategic sport, and the external and internal load metrics quantified by various studies substantiate the considerable physical and mental demands that players face. In sport and exercise, external load can be used to denote the work undertaken in some objectively measurable term, while internal load refers to the acute psychophysiological response to the external load (Impellizzeri et al., 2019).

Elite males playing in a FINA (now World Aquatics) international tournament covered on average 1613 ± 150 m per match, equivalent to 54 ± 6 metres per minute played (Melchiorri et al., 2010), while elite females playing in the 2007 World Championships covered an average of 699 ± 297 metres per match (Tan et al., 2009). In addition to swimming, depending on the tactical match situation in question, there are various activity patterns that athletes use during gameplay, which can include treading water, center offence, center defence, active offence, active defence, and wrestling/contacts (Botonis et al., 2019). Indeed, players frequently perform positional changes, from horizontal to vertical positions, with 4.6 ± 0.6 shifts per minute as described by Melchiorri et al. (2010). Moreover, changes in activity patterns every 6.2 ± 0.8 seconds have been documented by Tan et al. (2009). More recently, Canossa et al. (2020) analyzed games played by the top six male teams of the 2019 World Championships and found that, depending on the country, the mean duration of offensive sequences that occurred without time added was between 17.5 ± 8.6 and 23.5 ± 7.2 seconds, with between 3.4 ± 2.3 to 4.4 ± 2.5 passes per sequence. Time was added to the team's possession time 37% of the time, when the clock was reset after an exclusion foul, rebound, or corner throw (Canossa et al., 2022). In their analysis of all official matches played by an

Italian Serie A1 (premier division of Italian male national league) during the 2021-2022 season, Perazzetti, Dopsaj, Mandorino, et al. (2023) found that on average, per game, there were 207.1 ±26.3 successful passes, 7.2 ± 3.2 steals, and 12.3 ± 3.4 goals. Individual playing time appears to vary, with Melchiorri et al. (2020) finding that male field players at the 2015 and 2017 World Championships played an average of 17.4 ± 6.1 minutes, though with a range between 2.3 and 31.6 minutes (out of a total possible of 32 minutes). Elite males playing an international tournament before the 2019 World Championships recorded 14 ± 4 to 19 ± 6 minutes per game (Botonis et al., 2022); and in the men's tournament at the 2021 Olympics, players categorized as all-stars played an average 21.4 ± 5.3 minutes per match, while non-all-stars played 17.0 ± 6.1 minutes per match (García Ordóñez & Touriño González, 2022).

Notably, the intensity of game play is high. Excluding periods of easy or slow-speed swimming, all activity patterns are associated with a mean heart rate response of ≥ 87% of maximal heart rate (Botonis et al., 2019). Across a full season of 19 matches in the Serie A1 league, the mean session rating of perceived exertion (sRPE) of male water polo players was 7.3 ± 0.6 AU out of 10 (Perazzetti, Dopsaj, Sansone, et al., 2023). The elite males in the study by Botonis et al. (2022) reported a mean sRPE that ranged between 5.2 ± 1.2 and 8.4 ± 0.5 AU for the pre-World Championships international games they played, which the authors viewed as mirroring the challenge presented by opposing team. There has yet to be a quantification of the self-reported internal load associated with competition matches among female water polo players. Overall, competitive water polo matches are characterized by frequent, repeated high-intensity activity such that the most decisive actions in water polo depend greatly on anaerobic metabolism (Botonis et al., 2019). The duration of matches and the intermittent nature of efforts, alternating between maximal and lower intensity, indicate that water polo players require significant aerobic fitness, as well (Botonis et al., 2019). In contrast, there has been considerably less investigation of the mental demands of gameplay.

As in many other strategic ball sports, teams develop characteristic systems or styles of play, in addition to a gamebook of set plays (Bobrownicki et al., 2023; Canossa et al., 2022; Richards et al., 2017). Athletes are required to master these principles of play and adapt them to specific game situations and opponents, making further adjustments as the play unfolds. Together as a team, they must remain alert and attentive to multiple sources of information, integrating only what is relevant with agreed-upon team strategies to execute appropriately while adapting to a fast-paced and unpredictable context. Effectively negotiating this dynamic environment, while also under the time pressure of the shot clock, is essential for success. This is especially true as regular updates to the game rules are introduced to encourage more dynamic, creative, and "exciting" gameplay with more game actions and goals (Botonis et al., 2019; Canossa et al., 2022; Gardasevic & Joksimovic, 2020). As such, athletes' on-field decision making is a core element of the sport, and as for other team sports, skilful decision making lays the foundation of expert performance (Dicks et al., 2019).

1.2 Decision-making frameworks

In the domain of sports science, researchers have operationalized decision making as "the process of committing to a particular course of action" (Mascarenhas & Smith, 2011, p.245) or "the process of making a choice from a set of options" (Bar-Eli et al., 2011, p.6). While there exist many theoretical positions, some of the most prominent in the sports science literature include information processing, naturalistic decision making, embodied choice, and ecological dynamics.

1.2.1 Information processing

The information processing approach to cognition gained traction in the 1950s-1970s with the advent of the computer, drawing parallels between the functioning of a computer and human behaviour. A main assumption is the existence of a series of stages between stimuli and responses. Stimuli or events are first sensed and attended to, before a second stage called pattern recognition (Wickens & Flach, 1988) or perception (Wickens & Carswell, 2012), in which this information is associated with a meaningful interpretation based on experiences encoded in our memory (Wickens & Carswell, 2012). Following the processing of the perceived information, which involves interactions between working memory and long-term memory, in the context of sport, there is a selection of an action ("decision"), and finally, execution of this action (Tenenbaum, 2003; Wickens & Flach, 1988). The resulting responses, or consequences, serve as feedback that becomes new input as the process repeats. This perspective is also called a cognitivist or constructivist approach for its emphasis on the cognitive processes preceding motor action and the role of perception in constructing meaning from information in the environment through internal representations of reality (Williams et al., 1999). Information processing has been adopted to describe anticipation and decision-making processes on an individual athlete (Tenenbaum, 2003) and whole-team basis (Reimer et al., 2006). Athletes, once having attended to relevant cues and integrated this information with existing knowledge structures (French & McPherson, 1999) to update their mental model of the situation, can generate various possible courses of action and anticipate the potential consequences of each (Reimer et al., 2006; Tenenbaum, 2003). This will in turn allow them to make a selection while maintaining the possibility of switching to an alternative action (e.g., based on the behaviour of the opponent) (Reimer et al., 2006; Tenenbaum, 2003). Figure 1.1 depicts an example of the serial, representation- based information processing model.

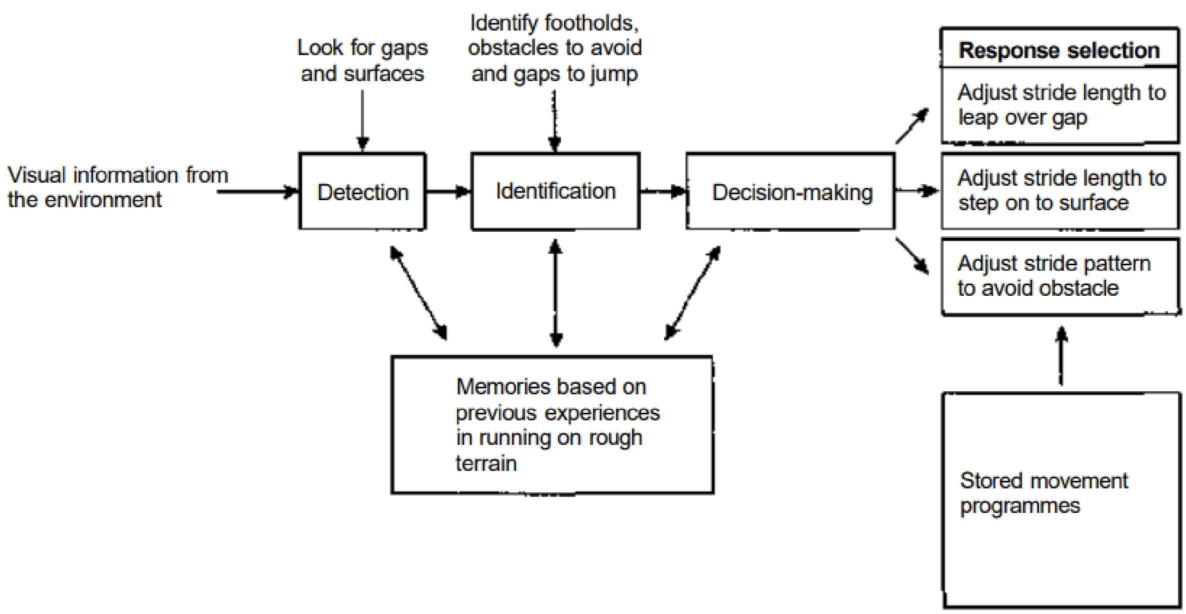

Figure 1.1. Model of information processing depicting how athletes may use internal representations for decision making. From "Indirect theories of perception and action" by A. M. Williams, K. Davids, & J. G. Williams (Eds), *Visual Perception and Action in Sport*, 1999, London, UK: Taylor & Francis. Copyright 1999 by Taylor & Francis Informa UK Ltd - Books. Reprinted with permission.

The environment (e.g., teammates, opponents, coach) contribute to the feedback that will inform subsequent decisions (Reimer et al., 2006). In situations of extremely short temporal constraints, a response can be generated through automatic and unconscious access of knowledge structures (declarative and procedural) and motor schema, which are generalized motor programs existing in memory scalable to the environment (Schmidt, 1975; Tenenbaum & Bar-Eli, 1993). There is an emphasis on the role of memory and knowledge structures or mental models that athletes possess and share with their teammates (e.g., about one's team and the opposing team) that allow them to effectively and efficiently interpret picked-up cues, anticipate consequences to potential actions, and ultimately, choose an appropriate course of action (Reimer et al., 2006; Tenenbaum, 2003; Williams et al., 1999).

1.2.2 Naturalistic decision making and Recognition-primed decision models

Naturalistic decision making can be defined as "the way people use their experience to make decisions in field settings" (Zsambok, 1997, p.4). The term first appeared in 1989, during a conference that assembled researchers who had taken non-traditional approaches to studying decision making (Zsambok, 1997). In the 1980s, it had become clear that people do not operate based on generated probability and utility estimates combined with systematic comparisons of options, and are not rational nor "optimal" decision makers (e.g., Kahneman et al., 1982). Researchers were finding that formal models of decision making were insufficient to explain or predict real-world behaviour (Zsambok, 1997). These scientists migrated away from laboratory designs that tested statistical/mathematical models of optimal choice strategies and instead turned to studying the decision making of experienced people in their natural environments or in representative simulations of their environments (Klein, 2008). A key contribution of the 1989 conference was the identification of several core contextual factors that influence real-world decision making, which led to a more comprehensive definition:

> The study of naturalistic decision making asks how experienced people working as individuals or groups in dynamic, uncertain, and often fast-paced environments, identify and assess their situation, make decisions and take actions whose consequences are meaningful to them and to the larger organization in which they operate (Zsambok, 1997, p.5).

Skilled decision making is based on tacit knowledge: having a wealth of patterns accumulated with experience, finer perceptual discrimination, and thus greater situational awareness and rich mental models (Klein, 2015). Unlike serial models of decision making, naturalistic decision making proposes that there are rarely conscious or subconscious processes of generating and choosing from several options (Klein, 2015). Nine models of naturalistic decision making were documented at the 1989 conference (Lipshitz, 1993), and the one that has received the most attention in sport science research is that of recognition-primed decision making (Figure 1.2). This model is a balance of intuition and analysis, corresponding to fast, unconscious system 1 and slow, deliberate system 2 of dual-process accounts of cognition (Evans, 2008; Klein, 2008). In line with the notion of satisficing (Simon, 1957), decision making is conceptualized as a pattern-matching process in which the first option that is good enough is chosen, rather than waiting to find the optimal option (Klein, 2008). When the current situation is a straightforward match to a familiar case, the person will execute the typical course of action (Klein, 2008). When there is uncertainty related to the situation, an individual will seek to diagnose it, a process that aims to establish a plausible explanation for the events to better understand what is going on (i.e., increase situation awareness). Strategies used in diagnosing include feature matching: categorizing a situation based on the relevant features, and story building: mental simulation that looks backwards in time to derive a causal explanation (Klein, 1997). Mental simulation is also used in more complex situations to project a potential course of action forward in time and assess if it will run into problems or needs to be adapted, or if other actions need to be considered (Klein, 1997, 2008).

Though naturalistic decision making originated to understand the decision making of people working as military commanders, pilots, nurses, firefighters, nuclear power plan operators, and similar occupations (Klein, 2008), the time pressure, high stakes, situational uncertainty, and experience level of the decision makers are also characteristic features of high-performance sport. Indeed, self-confrontation interviews held among professional male (Macquet, 2009) and university and college-level female (Fortin-Guichard et al., 2021) volleyball players, expert male youth hockey players (Mulligan et al., 2012), professional male soccer players (Kermarrec & Bossard, 2014), and elite male badminton players (Macquet & Fleurance, 2007) highlight how athletes' decision making is contextual and involves recognition of current situations and making links to previous experiences.

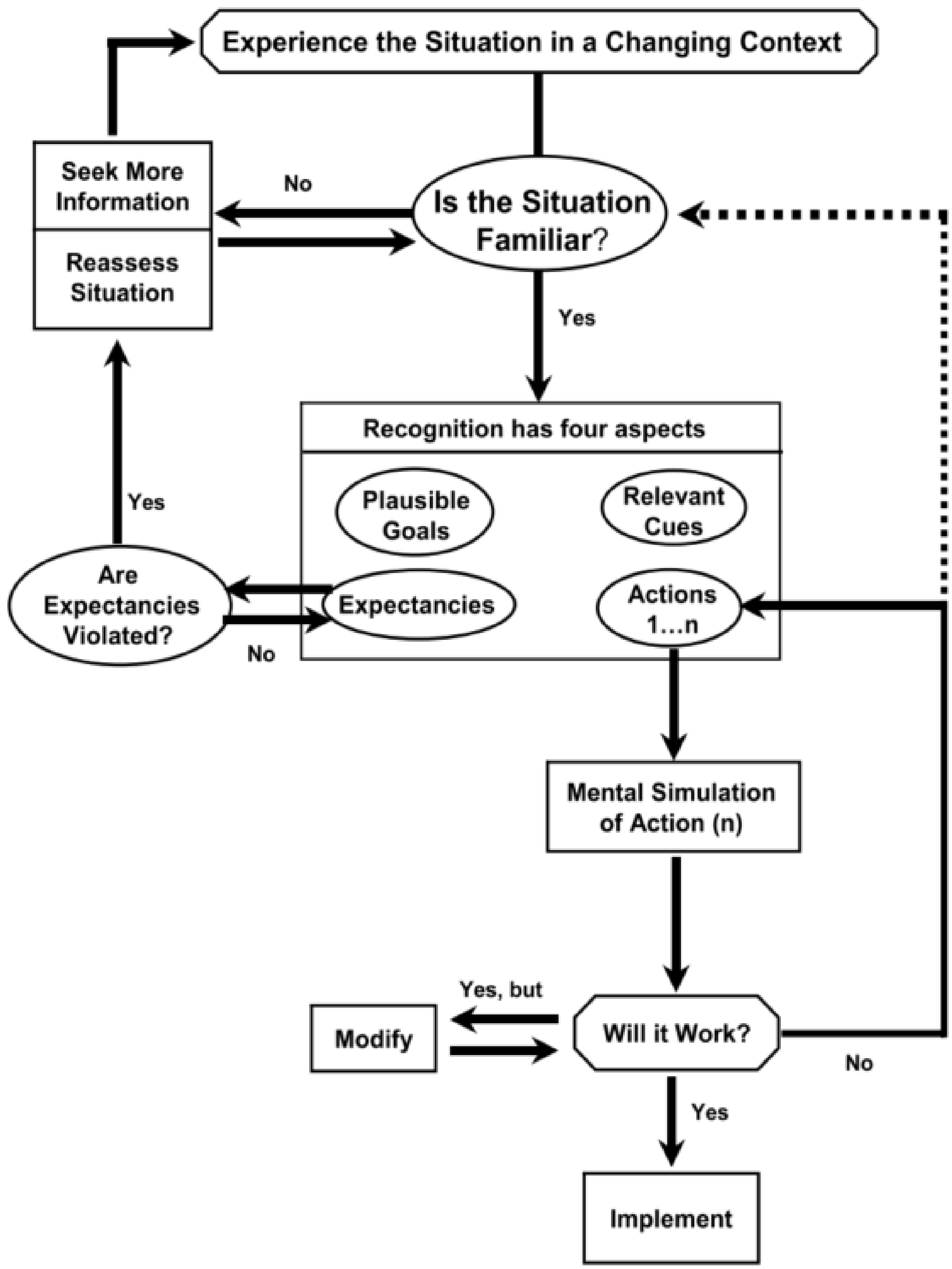

Figure 1.2. Model of recognition-primed decision making. From "A recognition-primed decision model of rapid decision making" by G. Klein, in G. A. Klein, J. Orasanu, R. Calderwood, C. E. Zsambok (Eds), Decision making in action: Models and methods, 1993, Norwood, NJ: Ablex Publishing Corporation. Copyright 1993 by Praeber, an imprint of Bloomsbury Publishing Plc. Reprinted with permission.

1.2.3 Embodied choice

In recent years, the concept of embodied choice has become more prominent in sport psychology. It can be defined as a choice "in which the current and stored sensorimotor processes serve as an important cue in the judgement and decision-making process of choosing what to do and how to do it" (Voigt et al., 2023, p.48). Here, a choice refers to the outcome of a decision-making process (Voigt et al., 2023). Embodied choice is a perspective that rejects classical serial conceptualizations of decision making that distinguish sequential stages of perception, cognition, and action; it instead integrates embodied cognition and simple heuristics.

Embodied cognition views cognitive processes as occurring within an individual's physical body that interacts with the world; in other words, aspects of the body other than the brain significantly influence cognition (Schneegans & Schöner, 2008; Wilson & Foglia, 2017). The term "embodied" corresponds to the fact that we interact with our environments with our bodies and that these experiences influence how we make decisions. Sensorimotor experiences refer to information integrated from our sensory system (i.e., vision, audition, tactile stimulation, olfaction, gustation) and our motor system (i.e., central and peripheral nervous system structures that support movement) (Voigt & Raab, 2024). Given that our sensorimotor experiences are tied to our individual anatomical and physiological constraints and capacities, our physical attributes can influence our decision-making processes (Voigt et al., 2023). While the sensorimotor experience of our current sensations and muscle activations play an important role in our decision making, in addition to these "online" effects, there are also "offline" effects, which describe the influence of self-stored experiences of movements learned and performed previously (Schütz-Bosbach & Prinz, 2007; Voigt et al., 2023). Internal representations that are fed from motor-related processes (e.g., mental simulation, imagery of movements) also generate sensorimotor experiences (Gentsch et al., 2016) and therefore can also affect embodied choices (Voigt et al., 2023).

Another core tenet of embodied cognition is that of cognition being situated (Voigt et al., 2023). Situated cognition is contextual, occurring in the real world, bound to task-relevant input (e.g., information the person perceives and that affects the ongoing cognitive processing) and output (e.g., motor actions the person performs that influences the environment in ways that in turn can affect the current task by changing the sensorimotor information) (Wilson, 2002). Thus, perception and action are not discrete stages in a sequence, but bidirectional, continuous, and intertwined, without clear boundaries between the processes of decisions and actions (Gordon et al., 2021; Yoo et al., 2021). For example, in water-polo, in a breakaway tactical situation, an athlete may be swimming towards the net, moving to maintain the numerical advantage before a choice is made about whether she will shoot or pass ("act while deciding"; Gordon et al., 2021). It is also possible to "decide while acting" (Gordon et al., 2021), such as if the player stands up to assume a vertical position with her legs under her in preparation to shoot, but as she is faking, changes her mind in response to changes in the dynamic situation (e.g., the movement of the goalie in response to her faking, leaving a teammate wide open; or an opponent closing in), and instead chooses to pass. In this way, actions as output of decision-making processes are not always the final end product but continue to influence decision making through a bidirectional relationship with incoming information.

In addition to deriving central assumptions from embodied cognition, the perspective of embodied choices also draws from simple heuristics (Gigerenzer & Goldstein, 1996; Gigerenzer & Todd, 1999; Raab, 2012) to describe how decisions can be made under conditions of time pressure and uncertainty (Raab, 2017; Voigt et al., 2023). A heuristic is a rule of thumb, which the Oxford English Dictionary defines as "an approximate method for doing something, based on practical experience rather than theory." It can be more specifically described as "a strategy that ignores part of the information, with the goal of making decisions more quickly, frugally, and/or accurately than more complex methods" (Gigerenzer & Gaissmaier, 2011, p. 454). Decision makers rely instead on a few task-relevant cues (i.e., sources of information). Familiar examples are "take-the-first" or "take-the-best" (Bennis & Pachur, 2006). In a situation where a water polo player has the ball in front of the net and has the options of shooting or passing the ball to one of the five teammates, according to the "take-the first" heuristic, the athlete picks the first generated option for what to do and how to do it rather than generating all options and deliberating to select the optimal one. For "take-the-best", the individual begins with the cue with the highest validity (i.e., the most correlated with the outcome to be predicted) and compares the options (Bennis & Pachur, 2006). Once there is a cue that discriminates between options, the search for information is ended and the person chooses the option with the higher value of the cue (Gigerenzer &

Gaissmaier, 2011). Using the same example, the first cue could be defensive coverage, and if there are multiple teammates who are open, the next cue could be shot angle. If one teammate is in a position with a better shot angle than the others, then the decision maker will choose to pass to that particular teammate. Simple heuristics are the way by which an athlete is able to choose what to do and how to do it in unpredictable conditions even when they have mere milliseconds to respond appropriately. Congruent with the main ideas of embodied cognition, heuristics are situated (Gigerenzer & Gaissmaier, 2011), and the effectiveness of using our sensorimotor experiences in the decision-making processes will depend on how valid they are as cues in the current context (Raab, 2012; Voigt et al., 2023).

Thus, an embodied choice can be understood as arising from a rule of thumb that athletes can follow to choose an option that satisfies the needs of the current situation, and whose process is informed by the individual's sensorimotor representations – online and/or offline (Raab, 2012; Voigt et al., 2023).

1.2.4 Ecological dynamics

The ecological dynamics approach combines Gibsonian ecological psychology with dynamical systems in describing decision making in sport. Core to ecological psychology is the idea that the ecosystem consists of the performer and the environment, with the link between the two being reciprocal (Gibson, 1979a). Behaviour that arises from cognitive processes does not come from one actor (i.e., the performer) in this relationship, but rather is attributable to the individual-environment system (Araújo et al., 2006; Gibson, 1979b). Nonlinear dynamics is a branch of physics that studies systems whose behaviour may appear unpredictable or chaotic yet is not random. These concepts are applied to understand the ever-changing nature of the person-environment interactions and consider decision making as a complex process occurring over time and expressed by actions (Araújo et al., 2006; Beer, 2003). Actions are considered to be self-organized, generated by the dynamic interactions of multiple constraints within the individual-environment system, and not by external (e.g., outside instructions) or internal (e.g., predetermined in one's mind) processes (Raab & Araujo, 2019). Through the detection of information in their environment and the calibration of their action capabilities to their environment (which includes the people and objects in it), performers are perceptively attuned to affordances (i.e., opportunities for action), which will in turn guide their behaviour (Davids & Araújo, 2010; Gibson, 1979b). For instance, a water polo player's ultimate action with the ball would be shaped by defensive coverage, the positioning of teammates, perceived shooting skill, shot clock time and score, emotional state, among other constraints. In the context of team gameplay, with practice, players become attuned to shared affordances and are able to coordinate and adapt according to the behaviour of teammates and opponents (Araújo et al., 2023). Thus, decision making is "emergent" based on our interaction with the environment (Araújo et al., 2006; Gibson, 1966, 1979a).

Importantly, perception is thought to be direct (Gibson, 1966), derived solely from the information available, without an intermediary (e.g., internal knowledge structures, mental representations) that *re*-presents the world in meaningful or behaviourally-relevant terms (Araújo et al., 2019). In other words, sensory data is sufficient without the need for past knowledge, interpretation, or inference, and performers perceive the environment directly in terms of the actions available to them (Araújo et al., 2019; Gibson, 1966). This is in contrast with constructivist perspectives that propose that how we perceive the environment is an interpretation that is influenced by past experiences and expectations, and in the case of embodied choice, involve a matching within the brain of perceptual representations with action representations (Raab & Araujo, 2019). Like the embodied choice approach, however, individuals are actors within their particular environment, and there is an emphasis on the coupling of perception and action: the reciprocal relationship between perceptual and motor processes that allows performers to act based on the information in the environment (Gibson, 1979a; Raab & Araujo, 2019). Decision making is conceptualized as guiding our interactions with the environment towards a goal through a cyclical process of perception and action that uses information from both the environment and that it itself generates (Araújo et al., 2006; Gibson, 1979a). Accordingly, successful decisions rely on our efficiency in picking up relevant information (i.e., level of attunement) and the corresponding calibration to it (Araújo et al., 2006) (Figure 1.3).

Table 1.1 summarizes and compares key characteristics of the four decision-making frameworks presented

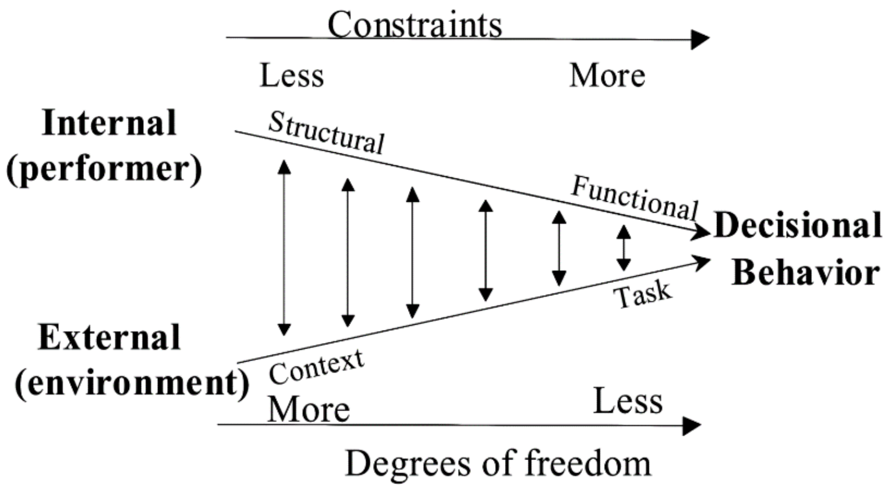

Figure 1.3. Emergent decision making guided by constraints. From "The development of decision making skill in sport: An ecological dynamics perspective" by D. Araujo, K. Davids, J. Y. Chow, & P. Passos, in D. Araujo, H. Ripoll, M. Raab (Eds), Perspectives on cognition and action in sport, 2009, New York, NW: Nova Science Publishers. Copyright 2009 by Nova Science Publishers. Reprinted with permission.

Table 1.1. Key characteristics of representational and non-representational models of decision making presented above.

	Representational			Non-representational
	Information processing	**Recognition-primed decision making**	**Embodied choice**	**Ecological dynamics**
Perception	Indirect – of cues			Direct – of affordances
			Continuous, coupled, and bidirectional with action	
Environment	Provides cues, which are sources of information, that are cognitively processed/mentally represented			Provides specifying information, that reveals affordances
			Situates cognition	Reciprocally linked to the performer, as part of the performer-environment system
Decision	Deliberate and optimal	Satisficing		Emergent
	Results from a comparison between generated options	Based on experience-based intuition and recognition	Derived from simple heuristics	The strongest attractor (i.e., stable system state) for the performer-environment system at a given moment
Experts	Have increased efficiency and effectiveness of domain-specific information processing, thanks to elaborate mental representations and enhanced memory systems (Eccles, 2020)	Are distinguished by their tacit knowledge. They possess rich repertoires of patterns acquired with experience, are able to make fine discriminations invisible to novices, have sophisticated mental models, have resilience to adapt to complex situations (Klein, 2015)	Develop domain-specific heuristics that rely on embodied cues, including sensorimotor experiences, to predict their own and others' actions in a flexible, fast, and frugal manner (Raab, 2017; Voigt et al., 2023)	Are attuned to specifying information, achieving intended performance goals by continuously functionally adapting their behaviour to dynamic and interacting constraints (Seifert et al., 2013)

1.3 Evaluating decision making

Measurement of athletes' strength and fitness capacities is ubiquitous and is necessary to identify opportunities for improvement, quantify the efficacy of an intervention, monitor capacities over time, and compare between athletes. For decision-making skill, there is similar interest in those objectives. Though it is a complex endeavour, researchers have nonetheless attempted it through the investigation of decision-making tasks in both laboratory and match-play settings. These tasks require athletes to decide what and/or how to do it, involving action selection with or without its execution (Iskra et al., 2024).

1.3.1.1 Laboratory-based assessments

A recent scoping review of 371 decision-making tasks found that the most common were video-based tests (Iskra et al., 2024). These are favoured for their applicability within the controlled environments that researchers often seek to create. These tests typically consist of video clips of game situations or actions that are played through until frozen or occluded, at which point athletes must respond according to the appropriate action to take. Besides this basic premise, there is significant variation in the structure of video-based tests in how the videos are presented and in the response modality of the participant. Elements of video presentation include the viewing perspective, such first person (e.g., De Waelle, Warlop, et al., 2021) or third person (e.g., Farahani et al., 2020); and the format of the video delivery, such as on a television (e.g., Rosch et al., 2021), life-size projection (e.g., Vaeyens et al., 2007), immersive curved projection screen (e.g., Klatt & Smeeton, 2021), or through virtual reality (e.g., Loiseau Taupin et al., 2023). The range of participant responses include marking their decision on paper (e.g., Nimmerichter et al., 2016), verbally responding (e.g., Pagé et al., 2019), clicking a mouse (e.g., Lorains et al., 2013a), and performing a sport-specific action (e.g., McMorris et al., 2000). In terms of evaluation, points may be attributed binarily (i.e., decisions considered as correct or incorrect; e.g., Murr et al., 2021) or on a scale (e.g., Bennett et al., 2019) with three to five increments based on the appropriateness of the response.

Quite often, studies that include video-based decision-making tests aim to make comparisons between groups of different playing calibre. For example, research in soccer (Bennett et al., 2019; Machado & Teoldo da Costa, 2020; Murr et al., 2021; Natsuhara et al., 2020; Vaeyens et al., 2007; Vítor de Assis et al., 2020), Australian football (Breed et al., 2018; Lorains et al., 2013a; Woods et al., 2016), and basketball (Rosch et al., 2021) all compared athletes to a group characterized as lower caliber (Breed et al., 2018; Lorains et al., 2013a; Machado et al., 2022; Murr et al., 2021; Natsuhara et al., 2020; Vaeyens et al., 2007; Vítor de Assis et al., 2020; Woods et al., 2016) or as novices/inexperienced (Bennett et al., 2019; Rosch et al., 2021; Vaeyens et al., 2007). Results often confirmed hypotheses of superior performance among the higher-caliber group (Bennett et al., 2019; Machado & Teoldo da Costa, 2020; Murr et al., 2021; Natsuhara et al., 2020; Rosch et al., 2021; Vaeyens et al., 2007; Vítor de Assis et al., 2020; Woods et al., 2016), but were sometimes unable to clearly distinguish between the groups and/or pointed to greater nuances (Bennett et al., 2019; Breed et al., 2018; Lorains et al., 2013a; Murr et al., 2021; Vaeyens et al., 2007).

Video-based decision-making tests have also been used to investigate the effects of a manipulated variable, such as physical or mental stress (Hepler, 2015; Hepler & Andre, 2020), and fatigue (Alder et al., 2021; McMorris et al., 2000; Royal et al., 2006; M. R. Smith et al., 2016). In these studies, which included both between-group or within-subject designs, participants completed the video-based tests after a physical (Alder et al., 2021; Hepler, 2015; Hepler & Andre, 2020; McMorris et al., 2000; Royal et al., 2006), cognitive (Alder et al., 2021; Hepler, 2015; Hepler & Andre, 2020; M. R. Smith et al., 2016), or combined physical and cognitive task (Alder et al., 2021). Participants' decision-making accuracy and/or reaction time was compared to performance in a non- and/or less fatigued state (Alder et al., 2021; McMorris et al., 2000; Royal et al., 2006; M. R. Smith et al., 2016), or to performance following a different experimental condition (Alder et al., 2021; Hepler, 2015; Hepler & Andre, 2020). Decision making was sensitive to the experimental manipulation in each of these studies except that by McMorris et al. (2000). Before and after i) an incremental test to exhaustion and ii) an incremental test to their epinephrine threshold, male college soccer players performed a video-based decision-making test that consisted of watching offensive plays and responding verbally as well as by kicking a soccer ball towards the appropriate target (McMorris et al., 2000). The authors suggested that the reason there were no significant differences between the three conditions was due to a combination of the relative simplicity of their task (essentially a 3-choice reaction time test) and the fact that testing took place after the exercise rather than during (McMorris et al., 2000). This is indeed an astute critique: during matches, athletes are required to exhibit optimal decision making while simultaneously exerting themselves physically. This contrasts with many designs in which the cognitive task is presented after each condition, while the participant is at rest. The dual-task paradigm would thus be of relevance for the study of decision making among athletes.

Dual-task designs have frequently been employed among healthy, non-athlete adults to examine cognitive performance. Generally, there appears to be exercise-intensity-related effects on executive functioning. Executive functions are cognitive control processes that support goal-directed behaviour that are classically separated into the functions of inhibition (withholding a prepotent response and controlling attention), cognitive flexibility (thinking creatively; switching between tasks), and information updating/working memory (Diamond, 2013; Miyake et al., 2000). There tend to be facilitative effects on executive functioning occurring at moderate exercise intensities and impairment at high exercise intensities (Audiffren, 2016; Cantelon & Giles, 2021; McMorris et al., 2016; Mekari et al., 2015; Zheng et al., 2021) – albeit with what seem to be interactions with exercise duration (Schmit & Brisswalter, 2020) and task type (Cantelon & Giles, 2021; McMorris & Hale, 2012). Notably, cardiovascular fitness has been demonstrated to moderate the change in executive functioning performance, with decreased or less consistent performance during dual-task compared to single-task conditions (Goenarjo et al., 2020) or during high-intensity compared to moderate-intensity exercise (Labelle et al., 2013; Labelle et al., 2014) among lower-fit individuals only. This spawns the question of if athletes' patterns of cognitive performance during different exercise conditions may differ from those of the general population, on the basis of higher levels of aerobic fitness. All this, combined with the finding that executive functioning performance at rest has been shown to only weakly predict executive performance during submaximal exercise (Faria et al., 2021), justifies expanding our understanding by examining athletes' decision making during exercise.

Three groups have studied soccer players' decision making at different exercise intensities using a video-based test (Fontana et al., 2009; Klatt & Smeeton, 2021; McMorris & Graydon, 1996; McMorris & Graydon, 1997; T. McMorris et al., 1999). In contrast to findings of impaired cognitive performance at high exercise intensities exhibited by healthy, non-athlete adults, athletes' accuracy and reaction times were either no different or better at high or maximal exercise compared to a rest condition. As an alternative explanation to fitness level, the nature of the task may be relevant for explaining these differences: some theories emphasize the specificity of athletes' expertise, with it presenting itself most prominently in sport-specific tasks (Kalen et al., 2021; Mann et al., 2007). It then becomes interesting to examine the exercise-cognition relationship among athletes for both domain-general and domain-specific tasks. There have, however, not been any studies that examine, during exercise, athletes' performance on a sport-specific decision-making task as well as on a domain-general cognitive task. Furthermore, the current literature on dual tasking, both among athlete and non-athlete samples, exclusively uses continuous, constant-load exercise modalities, whereas an investigation of decision making during a modality such as high-intensity interval exercise would be relevant considering the demands of many team ball sports, like water polo.

Therefore, we aimed to address these gaps in two steps. **First, given the absence of a standardized format for video-based decision-making tests, in our first study, we sought to create a test for water polo and assess its construct validity and test-retest reliability. We hypothesized that the test would be able to discriminate between water polo players based on their caliber, and that performance would be similar when the test was repeated. Subsequently, we examined performance on the water polo video-based test during different exercise conditions, also including a domain-general cognitive task in the study design to generate more understanding of the nature of the exercise-cognition relationship among athletes. The main purpose of the second study was to examine the effects of exercise intensity and modality on cognitive performance, and we expected that cognitive task performance would be impaired at high intensities for the domain-general Stroop task but not for the domain-specific water polo video-based task.**

1.3.1.2 On-field assessments

The experimental control, relative simplicity, and low resources associated with video-based tests may be a few reasons for their popularity in studying the effects of a given independent variable. However, it is important to consider that while results from studies that employ them may have informative value, video-based tests may be insufficient alone if the objective is to understand players' decision making – and factors that influence it – in the context of real match play. Specifically, there are limitations to the "ecological validity" of video-based tests in evaluating decision making. Originally coined by Egon Brunswik (1956), the term "ecological validity" was used to refer to the degree of statistical correlation between a proximal cue, i.e., information available in the environment (such as an experimental stimulus), and the distal variable, or target, to which it is related (what the experimental stimulus is meant to represent) (Brunswik, 1956). Thus, ecological validity denoted the correspondence between the cues in the experimental situation and the real world. Subsequently, ecological validity was defined as "appropriate generalization from the laboratory to nonexperimental situations" (Orne, 1962, p. 776), and the idea of generalization to naturalistic/real-life settings was further reinforced when it was used in this meaning by Ulrich Neisser (1976), the "father of cognitive psychology". Indeed, in the field of sport psychology, Davids (1988) proposed to define ecological validity as "a transient phenomenon characterized by informed and systematic attempts to analyze actual behaviour within specific environmental contexts, utilizing unobtrusive, realistic, and reliable methods of investigation" (p. 127). In fact, this conceptualization of ecological validity as the study of behaviour under sport-specific task constraints corresponds with Brunswik's (1956) notion of representative design (Araujo & Davids, 2015; Pinder et al., 2011): it describes experimental conditions, including the cues presented, that represent the environment to which the results should apply. In sport psychology, this can be understood as ensuring that characteristics of the experimental task reflect those present in the performance/training environment, and that specific relations between the participant and the environment are maintained (Pinder et al., 2011). For decision-making tasks specifically, ecological validity/representative design can also be reflective of the level of cognition-action interaction (Iskra et al., 2024). Athletes' decision making during matches occurs on a dynamic time scale, where options emerge and are considered as time goes on, instead of all being presented at once (Iskra et al., 2024; Townsend & Busemeyer, 1995).

The corresponding phenomenon of deciding while acting, integrating changes in the environment continuously into the decision process, is indicative of a high degree of cognition-action interaction (Iskra et al., 2024).

From this perspective, video-based tests, which may lack representativeness, may be viewed through a more critical lens. Videos that, for example, use third-person perspectives or show players of different caliber do not allow participants to pick up the same task-relevant information as in real life. Requiring athletes to make a choice from a preset array of options transforms the task into a static and serial assessment of decision making (Iskra et al., 2024). Furthermore, responses such as pressing a button or verbalizing an answer disregard the sensorimotor experiences and capabilities of the individual. Recalling common tenets of embodied choice and ecological dynamics: the interdependent nature of perception and action, and the interactional component with the environment, are core to decision making (Raab & Araujo, 2019). Thus, the typical perception and action relationship that underlies decision making is absent or disrupted.

In the study of match-play decision making, and the effects of different variables, some researchers have indeed turned to designs that are more representative and that maintain the key links between perception and action. The decision making of male (Fortes et al., 2020; Fortes et al., 2019; Fortes et al., 2018; Gantois et al., 2020; Mitrotasios et al., 2021; Romeas et al., 2016; Trecroci et al., 2020) and female (Gabbett et al., 2008) soccer players has been assessed, typically during small-sided games and simulated matches, though one study examined a real match (Fortes et al., 2018). Male youth volleyball players (Fortes, Fonseca, et al., 2021), male and female amateur boxers (Fortes, Gantois, et al., 2021), and elite female youth basketball players (van Maarseveen et al., 2018) have also been assessed during simulated matches (Fortes, Fonseca, et al., 2021; Fortes, Gantois, et al., 2021) or small-sided games (van Maarseveen et al., 2018). While some examined passing decision making only (Fortes et al., 2020; Fortes et al., 2019; Fortes et al., 2018; Gantois et al., 2020), others investigated all offensive actions involving the ball: passing, shooting, and dribbling for the studies on soccer (Gabbett et al., 2008; Mitrotasios et al., 2021; Romeas et al., 2016; Trecroci et al., 2020; van Maarseveen et al., 2018), or passing and attack for the study on volleyball (Fortes, Fonseca, et al., 2021). The boxers were judged on both attack and defense actions (Fortes, Gantois, et al., 2021). In all cases, though, decision making was assessed retrospectively by experts who judged the action in a binary way as appropriate or inappropriate according to criteria borrowed from or similar to that used by Gabbett et al. (2008) (Table 1.2). Subsequently, a decision-making index was usually calculated, as a ratio of appropriate decisions and the total number of decisions (Memmert & Harvey, 2008). More nuanced analyses of decision making were carried out in a study that aimed to investigate the level of transfer from video-based training to on-field performance of elite Australian Football players (Lorains et al., 2013b). In addition to other contextual details that were noted, decision-making quality was assessed on a point scale from 0-3 and the effectiveness (i.e., the outcome of the action) was coded according to one of 10 options (Lorains et al., 2013b).

Table 1.2. Decision-making coding criteria for soccer passing, shooting, and dribbling.
From "Does improved decision-making ability reduce the physiological demands of game-based activities in field sport athletes?", by T. J. Gabbett, J. Carius, and M. Mulvey, 2008, Journal of Strength and Conditioning Research, 22:6, p. 2030 (https://doi.org/10.1519/JSC.0b013e3181887f34). Copyright 2008 by National Strength and Conditioning Association. Reprinted with permission.

<u>Passing:</u> Was the decision to pass appropriate in the context of the given situation?
The player made a good decision when the pass went to a teammate who was open and it
(1) directly or indirectly created a shot attempt, or
(1) went to a teammate who was in a better position than the passer.
The player made a poor decision when the pass was
(0) made to a player who was closely guarded or when there was a defensive player positioned in the passing line,
(0) intercepted or turned over,
(0) made to an area of the field where no teammate was positioned, or
(0) kicked out of the field of play.
<u>Shooting:</u> Was the decision to shoot appropriate in the context of the given situation?
The player made a good decision to shoot when
(1) they were open for the shot and it was uncontested.
The player made a poor decision to shoot when
(0) the shot was blocked,
(0) the shot was taken off balance,
(0) the shot was taken when one or more defensive players were in good position, or
(0) the shot was taken when it was contested.
<u>Dribbling:</u> Was the decision to dribble appropriate in the context of the given situation?
The player made a good decision to dribble when dribbling if it
(1) created space for teammates,
(1) created a scoring opportunity, or
(1) created space for the dribbler.
The player made a poor decision to dribble when they
(0) dribbled when the defenders were in good defensive position,
(0) dribbled into a supporting defender that was in good position, and this did not create space for the dribbler or teammates,
(0) dribbled out of the field of play,
(0) dribbled when the immediate defender was in a good position to defend the dribble, or
(0) dribbled without a purpose (i.e., not going anywhere).

1.4 Disruptors to decision making

Given that athletes' decision making is a core part of gameplay, being able to consistently assess skilful decision making can have important implications for a team's overall performance. This makes it relevant to consider the variables that may disrupt decision-making performance. Within the competition setting, where there are more intense physical and cognitive loads and greater pressure to perform, these factors include state fatigue and anxiety.

1.4.1 Fatigue

The effects of fatigue [1] on sport-related performance have been the subject of interest for many researchers, reflected in the numerous reviews, chapters, and editorials published in recent years. The general message conveyed is that fatigue has detrimental effects for decision-making performance (Costa et al., 2022; Dambroz et al., 2022; González-Víllora et al., 2022; Habay et al., 2021; Martin et al., 2018; McMorris, 2020; Pageaux & Lepers, 2016; Schampheleer & Roelands, 2024; Smith et al., 2018; Sun et al., 2021), but a closer look reveals more ambiguity that researchers have attributed to methodological differences or limitations (Dambroz et al., 2022; Habay et al., 2023; Habay et al., 2021; Holgado et al., 2020) or related to the primary energy pathway of the performance task (McMorris, 2020; McMorris et al., 2018; Pageaux & Lepers, 2018; Smith et al., 2018; Van Cutsem & Marcora, 2021; Van Cutsem et al., 2017). Strikingly, authors' operationalizations of fatigue are not always defined, and few (Costa et al., 2022; Habay et al., 2021; Pageaux & Lepers, 2016) have included a manipulation check for fatigue. These elements are particularly important given that there are many different definitions of fatigue that exist, with a lack of consensus. There is also a dichotomization of fatigue into "mental" fatigue and "physical" fatigue, with the majority of recent reviews concentrated on mental fatigue (Costa et al., 2022; González-Víllora et al., 2022; Habay et al., 2021; Holgado et al., 2020; Martin et al., 2018; McMorris, 2020; McMorris et al., 2018; Pageaux & Lepers, 2018; Smith et al., 2018; Van Cutsem & Marcora, 2021; Van Cutsem et al., 2017). Few researchers have included both fatigue from mental or physical exertion (Pageaux & Lepers, 2016; Skala & Zemková, 2022), and critical issues with lack of clear

[1] Unless otherwise specified, all uses of "fatigue" refer to state fatigue, which is temporary, in contrast with trait fatigue, which is experienced over a prolonged period of time (e.g., weeks to months, Behrens et al., 2022).

operationalizations and inclusion criteria may still apply (Skala & Zemková, 2022). Although there is support for physical and mental fatigue as separate constructs (Russell, Jenkins, et al., 2020), there is also considerable overlap, for example, in how prolonged cognitive exertion can reduce endurance exercise performance (Van Cutsem & Marcora, 2021). Furthermore, during sport match play, there are simultaneous physical and mental loads that can lead to fatigue. Focusing on just physical or mental fatigue can therefore impede a more integrated and practically-relevant understanding of how fatigue impacts sport performance.

Much of the existing knowledge of the effects of fatigue on sport performance largely concerns endurance performance or maximal effort physical performances (e.g., maximal strength and power). As discussed, these physical capacities are, however, only one component contributing to an athlete's skill execution in their sport. Understanding how fatigue affects perceptual-cognitive skills, which encompass the ability to extract relevant environmental information and integrate it with existing knowledge to execute an appropriate response (Marteniuk, 1976), is an important preliminary step to eventually determining how to resist negative fatigue-related effects on decision making. There is evidence of higher-level athletes displaying different brain activation patterns than their lower-level (Carius et al., 2023; H. K. C. Faro et al., 2020; Gao et al., 2023; Huang et al., 2023) counterparts, which has been suggested as indicative of greater neuronal efficiency (Du et al., 2022; Li & Smith, 2021). Additionally, compared to closed-sport athletes, who perform predetermined motor actions in relatively predictable contexts, open-skill sport athletes face greater perceptual-cognitive demands (Koch & Krenn, 2021). Some have demonstrated that these differences in sport demands could be reflected in their cognitive functioning (Koch & Krenn, 2021; Russo et al., 2022; Wang et al., 2013), with others finding no differences between open-and closed-sport athletes (Bravi et al., 2022; Vona et al., 2024) and suggesting that low sensitivity of the cognitive tasks used to detect sport type-related cognitive specificity could be a factor (Vona et al., 2024). Similarly, there is great diversity in the perceptual-cognitive tasks used in studies investigating how they are affected by fatigue, making it hard to interpret results as a whole. Thus, while it remains unclear if and how sport type influences cognitive functioning, and considering the particular importance of perceptual-cognitive skill for open-skill sport players, it is justifiable to investigate fatigue effects on perceptual-cognitive performance among this specific group of athletes. **To address these gaps, we aimed to conduct a scoping review to synthesize i) the methods used to induce and attest to the presence of fatigue; and ii) the methods used to assess perceptual-cognitive performance. We also aimed to iii) describe what is known about the effects of fatigue on perceptual-cognitive performance among open-skill sports athletes.**

In the context of sport competition, the potential role of fatigue on decision-making performance becomes even more relevant to consider. In water polo, there are reductions in playing intensity and distance covered as players near the end of the match (Botonis, Toubekis, & Platanou, 2016; Botonis, Toubekis, Terzis, et al., 2016; D'Auria & Gabbett, 2008; Galy et al., 2014; Melchiorri et al., 2010; Platanou & Geladas, 2006; Tan et al., 2009), which could be interpreted as evidence of the development of fatigue (Botonis et al., 2019). Botonis, Toubekis, Terzis, et al. (2016) also found that high-level male water polo players had decreased repeated sprint ability, handgrip strength, 400-m swim time, and shooting accuracy after non-official competitive matches compared to before. Although these results used simulated matches, involved players who played the entire duration of the game without substitution, and/or were from competitive matches with old rules and different quarter durations (D'Auria & Gabbett, 2008), there is substantial evidence across sports that the significant levels of exertion required to meet the demands of competitive match play induce fatigue among athletes (Barte et al., 2017; Botonis, Toubekis, Terzis, et al., 2016; da Costa et al., 2023; Russell, Kelly, et al., 2020). They can also have effects that accumulate over consecutive matches during congested game schedules (Botonis et al., 2024; Garcia et al., 2023; Howle et al., 2019). Indeed, the motivational difference associated with the existence of consequences tied to the outcome of the match can influence athletes' technical and tactical behaviour (Maloney et al., 2018; Olthof et al., 2019) and result in especially high loads experienced during competition (Impellizzeri et al., 2019). Elite male water polo players preparing for the Olympics have reported greater subjective fatigue during a training camp and a simulated tournament period compared to before the camp (Botonis & Toubekis, 2023). Among youth female players, Brisola et al. (2023) found that their weekly internal load, measured as the sum of (session ratings of perceived exertion x training duration in minutes), was higher on average for the competitive phase compared to the general and specific preparatory phases (Brisola et al., 2023). Likewise, in a variety of other tactical team sports, metrics of external and internal load variables from competition often exceed those of training – even when training consists of small-sided games or simulated matches. For instance, among elite female netball players, PlayerLoad, as well as the number of accelerations, decelerations, and changes of direction per minute, were significantly greater for match play compared to all other types of practice drills, including small-sided games (Simpson et al., 2020). Similarly, various parameters related to number of accelerations, running distance, and average speed were greater for matches compared to simulated matches among semi-professional male rugby players (Doering et al., 2023). The physical demand of competition matches was also greater than that of training among elite female field hockey players (Gabbett, 2010) and elite female water polo goalkeepers (Clément et al., 2022), on the basis of more time spent in high- and moderate-intensity activities. There are congruent results concerning internal load, with higher heart rate-related metrics (Douglas et al., 2019; Montgomery et al., 2010; Simpson et al., 2020), estimated oxygen consumption (Montgomery et al., 2010), and ratings of perceived effort (Moreira et al., 2012; Murphy et al., 2016) for official matches compared to simulated matches or training.

The higher stakes of competing, relative to regular training, also impose particular emotional regulation demands. Combined with the higher attentional focus demands (e.g., to cope with external and internal distractors, adapting to unfamiliar opponents, etc.), these lead to greater cognitive loads as well (Russell, Kelly, et al., 2020). Indeed, players have reported higher levels of arousal and anxiety for official Taekwondo fights compared to training fights (Maloney et al., 2018); higher ratings of mental exertion and effort when competing (Maloney et al., 2018; Murphy et al., 2016); and the worst wellness scores (sleep quality, muscle soreness, fatigue, stress, and mood) on the day after game day, relative to all other days within a microcycle (Oliveira et al., 2023). Congested competition schedules, such as during tournaments or international competitions may present even greater challenges with media obligations, disruptions to sleep and nutrition routines, travel, and limited time for recovery between consecutive performances.

Considering what appear to be conditions and loads that are unique to the setting of competitive matches and tournament play, there is much to gain from exploring the potential influence of fatigue on decision-making performance in this specific context. Anecdotally, match-play fatigue can impair decision-making performance (Morgan et al., 2020; Schläppi-Lienhard & Hossner, 2015), but there remains a large gap in the literature. In studies that have quantitatively examined the effects of fatigue on decision making during game situations, authors have investigated the effects of mental fatigue on decision making by inducing fatigue beforehand and comparing subsequent playing to a non-fatigued condition (Fortes et al., 2020; Fortes, Fonseca, et al., 2021; Fortes, Gantois, et al., 2021; Fortes et al., 2019). However, despite a quantification of decision making in contexts representative of competitive match play, only mental fatigue was examined – and induced before the simulated match. These methods, along with the between-condition analyses, mean that there is still little known about if and how decision-making quality decreases in a naturalistic environment, over the course of a match and/or a tournament. Kempton et al. (2013) have perhaps come the closest to addressing this: they analyzed full-length male rugby competition matches and coded all attacking and defense skills from 0-5 based on execution and appropriateness. They compared performance between the first 5-min interval of each half to the two final 5-min periods of each half, as well as the peak 5-min period to the subsequent 5-min period and to the mean of all other 5-min intervals. The average skill rating was higher in the first 5-min interval of each half and in the penultimate 5-min interval of the first half compared to the last two 5-min periods of the second half, and was higher in the peak 5-min period compared to the subsequent period but not the mean of all other periods (Kempton et al., 2013). This approach of evaluating decision making over time seems appropriate to address the question of impaired decision making due to fatigue that develops throughout a match. Opportunities to expand include treating time as a continuous variable, using the data from all timepoints without averaging over periods, and examining decision making over multiple consecutive games played in a tournament. **Therefore, the objective of the third study was to evaluate decision making during real competition matches and examine if the hazard of decision-making errors increases as the match and as the tournament progress. On the basis that fatigue develops over the course of a match and accumulates during a tournament, we hypothesized that the hazard associated with making a poor decision would increase over time.**

1.4.2 Pressure

There are generally higher stakes at competition than during regular training, with a certain level of importance ascribed to the outcomes, thereby creating heightened feelings of pressure (Baumeister, 1984). Pressure can give rise to successful performances (Brown et al., 2017), but can also create conditions in which athletes may perceive there to be important consequences should they fail to meet environmental demands (Martens et al., 1990). This can lead to stress (Martens et al., 1990). Stress can be used to describe a process that involves our environmental demands, our appraisal of these in relation to our perceived resources, and our physiological, cognitive, and behavioural responses (Fletcher et al., 2006). One potential emotional response is that of increased state anxiety (Martens et al., 1990; Mellalieu et al., 2009): a current emotional state characterized by apprehension and tension, and associated with activation of the autonomic nervous system (Martens et al., 1990; Spielberger, 1966). It is distinguished from trait anxiety, which refers to one's predisposition for perceiving environmental demands as threatening and responding with reactions of state anxiety (Martens et al., 1990; Spielberger, 1966). In the rest of this thesis, "anxiety" will be used to refer to state anxiety. There are various models that have sought to explain the relationship between sport-related state anxiety and performance (Apter, 1982; Hanin, 2007; Hardy & Parfitt, 1991; Hull, 1943; Martens et al., 1990; Smith & Smoll, 1990; Yerkes & Dodson, 1908), and while debates rage on, there is agreement that sport-related anxiety has an influence on performance, with the effect being a negative or positive one depending on the situation and the individual's physiological, cognitive, and behavioural responses to it (Ford et al., 2017).

In the context of decision making, there has been significant attention on the potentially detrimental effects of anxiety on cognition and consequently, performance. While the directionality of anxiety-related effects may be context-specific, many agree that elevated levels of anxiety provoke changes in attention that can ultimately negatively impact decision making and sport performance. Attention can be understood as our selective pick up of information to guide behaviour, where behaviour can be bodily as well as mental actions (e.g., reasoning, recalling, etc.; Wu, 2023). The attentional control theory (Eysenck et al., 2007) builds on the view that we have two attentional systems: one, a top-down system influenced by knowledge, expectation, and current goals; and the other, a bottom-up, stimulus-driven system that responds to salient stimuli (Corbetta & Shulman, 2002; Posner & Petersen, 1990). It posits that anxiety impairs attentional control by creating an imbalance between these two systems: more attentional resources are allocated to the stimulus-driven system, and specifically to threat-related stimuli such as worrisome thoughts and task-irrelevant distractors like the crowd (Eysenck et al., 2007). The result of this shift in attention is decreased efficiency in inhibition (e.g., resisting disruption from irrelevant stimuli or responses) and shifting (e.g., optimally adapting the allocation of attention within and between tasks), and a greater susceptibility to distraction by task-irrelevant information at the expense of task-relevant information. Performance effectiveness (e.g., decision-making quality) can be impaired if no compensating strategies, such as greater effort, are applied (Eysenck et al., 2007).

An updated sport performance-specific model, attentional control theory: sport (Eysenck & Wilson, 2016), specifies that how pressure influences levels of state anxiety in the performance context depends on our attentional and interpretive biases. Attentional biases refer to our propensity to attend disproportionately to threat cues like previous errors or an opponent's good performance (Bar-Haim et al., 2007), while interpretative biases involve how we interpret situations as threatening or not, such as viewing an error as predictive of failure (Bishop, 2007). If high anxiety is experienced, as described by the original attentional control theory, if there are inadequate compensatory strategies, attentional control will be disrupted and performance impaired (Eysenck & Wilson, 2016).

Another perspective that examines disrupted decision making under pressure is that of reinvestment theory (Masters & Maxwell, 2008). Originally used to describe the phenomenon in which a desire to succeed under pressure leads to the conscious control of well-learned, previously automatic actions – to the detriment of motor execution (Masters & Maxwell, 2008), the theory has been applied to decision making. Decision reinvestment involves less efficient investment of cognitive effort, conscious monitoring of the decision-making process, and rumination over previous poor decisions (Kinrade et al., 2015). Like attentional control theory, the ultimate result is suboptimal allocation of attention and cognitive processing that may hinder performance.

On the field, however, decisions do not remain inside the heads of athletes: decision making manifests itself as an action. The integrated model of anxiety and perceptual-motor performance, often applied in the context of high-stakes decision making, considers this eventual motor component (Nieuwenhuys & Oudejans, 2012, 2017). Leaning on theories of embodied cognition (Beilock, 2008; Voigt et al., 2023), in this model, the operationalization of perceptual-motor behaviour resembles some conceptions of decision making: it is a repeating process that involves our perception of different action possibilities in our environments, selection of our preferred courses of action, and detection and use of information to coordinate our movements and execute these actions (Nieuwenhuys & Oudejans, 2012, 2017). It recognizes that goal-directed movements exist within the context of our environments. Consistent with other theories, anxiety provokes an upregulation or dominance of stimulus-driven control, to the detriment of goal-directed processes, with neurobiological changes (Bishop, 2008) that lead to more threat-salient attention (attentional biases) and interpretations (interpretational biases). The integrated model of anxiety and perceptual-motor performance also considers effects on the physical response, such as increased muscle tension (Coombes et al., 2009) or responses directed away from a stressor (Stins et al., 2011), and describes how the impact of anxiety on perceptual-motor behaviour depends on the interactions between attentional, interpretational, and physical response effects (Nieuwenhuys & Oudejans, 2012, 2017). As in attentional control theory (Eysenck et al., 2007), anxiety is predicted to decrease processing efficiency as individuals allocate resources and expend effort to compensate for potentially negative effects, with or without a drop in perceptual-motor performance effectiveness.

Empirically, male basketball players have demonstrated lower response accuracy on a video-based basketball choice reaction time task when under higher pressure (Kinrade et al., 2015). Similarly, male soccer players demonstrated shifts in gaze behaviour and worse performance of penalty shots when anxiety was induced (Wilson et al., 2009). Researchers have also examined passing decision making during a real game among male under-17 soccer players, and found pre-match anxiety ratings to correlate negatively with decision-making scores (Fortes et al., 2018). Pressure does not guarantee the development of anxiety and sport-related state anxiety is not unequivocally non-functional. However, there appears to be agreement that when these conditions do arise – conditions inherent to high-performance sport contexts – there is potential for there to be negative repercussions on decision making (Fortes et al., 2018; Kinrade et al., 2015).

1.5 Training decision making

With decision making performance holding such an integral role in strategic sports, when it falters during a match, there can be impactful consequences, including team collapse: "a sudden, collective, and extreme underperformance of a team within a competition…that interferes with the team's interplay, [resulting in] a low of control of the game, and ultimately the inability of the team to regain their previous performance level within the game" (Wergin et al., 2018). This description matches what Water Polo Canada staff had identified and which they attributed to fatigue-related decreases in decision-making quality. Fatigue may be just one piece of the puzzle, though. Indeed, interviews with professional athletes suggest that team collapse is more likely to occur when there is physical exhaustion, lack of attentional focus, increased pressure, and poor preparation (Wergin et al., 2018). Thus, while fatigue and pressure are key factors to consider in light of their pervasiveness in competition settings, there would be value in enhancing preparation for competition using a broader approach that includes, but is not limited to, targeting these variables. A relevant strategy may therefore be to develop resilient decision making: decision making that adapts successfully to disturbances (Southwick et al., 2014).

Despite the differences between representation-based and ecological training methodologies (Figure 1.4), there are also points of convergence between their methodologies (Lindsay & Spittle, 2024). In particular, both approaches to motor learning stress the importance of progressing towards representative, game-like situations that reflect the demands of competition (Lindsay & Spittle, 2024).

1.5.1 Representative training

Representative learning design is a framework that emphasizes that the training environment should represent the competition environment to maximize skill transfer (Pinder et al., 2011). The concept of representative learning design applies principles of Brunswik's representative experimental design to the design of interventions and training tasks (Pinder et al., 2011). Within the practice environment, as in experimental designs, task constraints should replicate those in the performance environment.

Constraints can be described as the characteristics, demands, and conditions that may restrict certain options while promoting other ones. The affordances (i.e., opportunities for action) associated with the design should be functional (i.e., relevant considering behaviour in the performance context) and allow for athletes to couple their actions to information sources that would exist in the specific performance environment (Pinder et al., 2011).

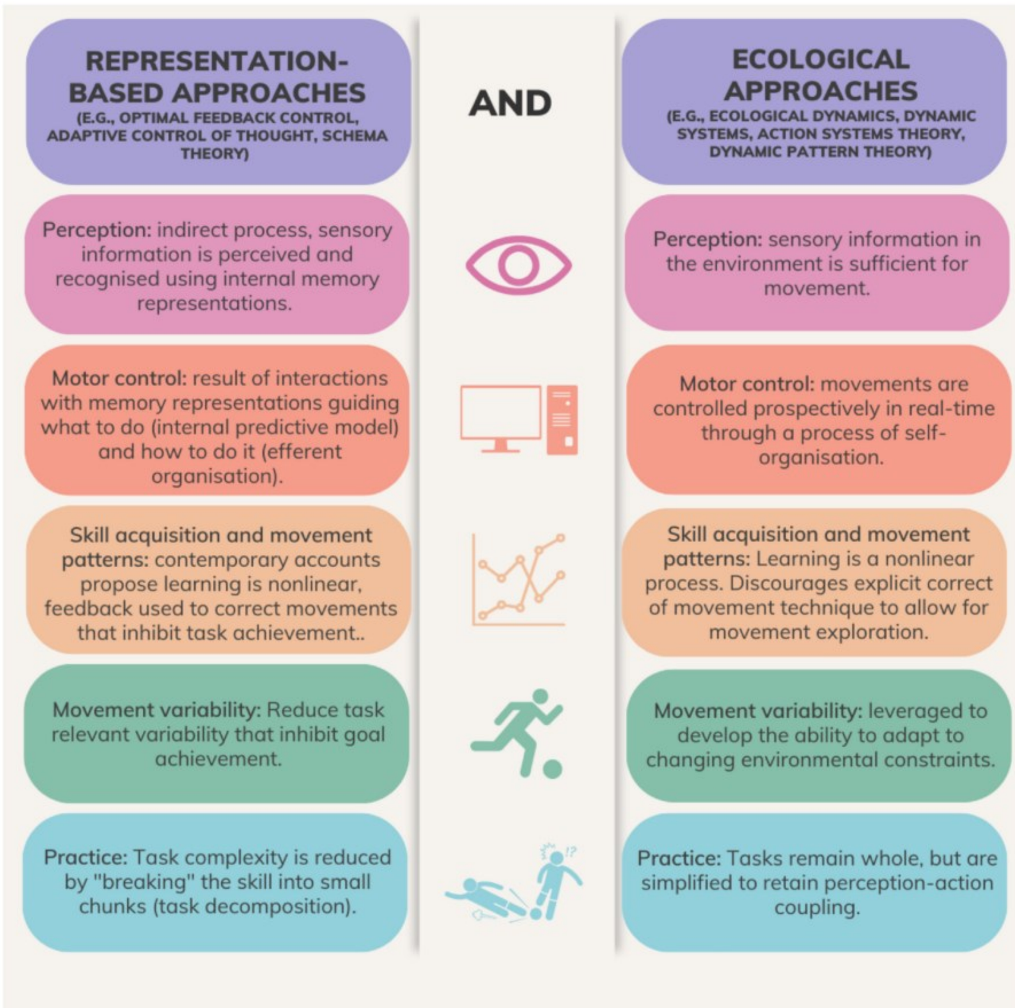

Figure 1.4. Key characteristics of theoretical underpinnings of representation-based and ecological approaches to coaching. From "The adaptable coach – a critical review of the practical implications for traditional and constraints-led approaches in sport coaching," by R. Lindsay and M. Spittle, 2024, International Journal of Sports Science & Coaching, 19(3), p. 1243 (https://doi.org/10.1177/17479541241240853). CC BY 4.0.

Representative learning design is a pillar of nonlinear pedagogy (Chow, 2013), which rests on core concepts of ecological dynamics (Correia et al., 2018) and conceptualizes athletes as complex neurobiological systems that behave purposively, relying on the interdependence between perception and action (Pinder et al., 2011). Despite its ecological origins or current associations, though, representative learning design is coherent and relevant across schools of thought. From an ecological dynamics view, representative designs allow athletes to perceptually attune to relevant information, which will in turn guide functional and adaptable actions (Renshaw & Chow, 2019). Within the model of naturalistic decision making, one example of a framework based on representation-based theories, representative designs are opportunities where athletes apply knowledge structures (e.g., the team's system of play) and hone team-specific shared mental models so that once in competition situations, they are able to execute effectively in a coordinated fashion (Richards et al., 2017). Indeed, if decision making is the targeted perceptual function of training, skill transfer to competition is predicted to be maximized the higher the degree of sport-specificity of the information the athlete has access to (i.e., stimulus correspondence), and the greater the degree of similarity between the behaviour in the training and the competition context (i.e., response correspondence) (Hadlow et al., 2018). Outside of these theoretical positions, interviews with elite and academy male Gaelic football players, professional male soccer players (Levi & Jackson, 2018), and expert-level volleyball players (Schläppi-Lienhard & Hossner, 2015) indicate that athletes perceive there to be a range of factors, such as personal performance, match importance, opposition attributes, coach instructions, score and time remaining, individual action capabilities, among others, that influence their decision-making during matches. Thus, representative designs may be used to expose teams to various information sources that they will encounter when competing, providing them the opportunity to master integrating them to make the appropriate decisions. This may in turn enhance preparation and performance consistency, and thereby reduce the incidence of team collapse.

Multiple theoretical and subjective perspectives support the value of representative designs in training, which leads to the question of how they can be created. Skill acquisition interventions documented in the literature are predominantly focused on closed skills in laboratory settings with low representativeness (Choo et al., 2024). Similarly, approaches such as variable practice (Schmidt, 1975), contextual interference (Shea & Morgan, 1979), structural learning (Hossner et al., 2016), and differential learning (Schöllhorn et al., 2010) have typically been implemented to target motor learning of closed skills in the same controlled conditions. More recently, though, a research group has investigated the benefit of differential learning on open soccer (Diogo Coutinho et al., 2018; Santos et al., 2018) and basketball (Mateus et al., 2015) skills. However, considering the context in which the work of this thesis is situated, the most appropriate method of creating representative training may be the constraints-led approach (CLA) (Renshaw & Chow, 2019). Water polo players are expected to execute and adapt tactics based on specific static and dynamic contextual information. Thus, the fact that constraints are manipulated intentionally in CLA – rather than randomly as in differential learning – means that constraints can be used to increase representativeness while remaining aligned with current coaching practices and specific team objectives.

1.5.1.1 Constraints-led approach

The CLA is a methodology with origins as an ecological perspective on motor control based on Karl Newell's (1986) model of interacting constraints, whereby through these interactions, the individual self-organizes and functional action solutions emerge (Renshaw & Chow, 2019). Thus, constraints are considered as the boundaries that shape self-organization. They are frequently categorized as individual, environmental, and task constraints (Newell, 1986) (Figure 1.5). Individual constraints include a person's unchangeable and changeable characteristics, such as their intentions, anatomy, confidence level, and fitness; while environmental constraints encompass physical and social attributes, including weather, playing surface, and crowd noise (Correia et al., 2018). Finally, task constraints include parameters such as the objectives, rules, and field size (Correia et al., 2018). Through intentional manipulation of constraints, coaches and practitioners can design training environments that are representative of the performance environment (i.e., possessing functional affordances and perception-action coupling) as well as expose athletes to specific conditions that they may experience – and against which they should be more resilient – at competition. The idea is to allow athletes to explore and develop performance solutions that are stable yet adaptable to the specific constraints of a given situation (Correia et al., 2018; Renshaw & Chow, 2019), including scenarios with greater physical, cognitive, and emotional demands. Indeed, in altering the characteristics and/or designs of small-sided games, researchers have demonstrated corresponding changes in players' technical-tactical behaviour (Díaz-García et al., 2023; Teune et al., 2022), physiological (Botonis et al., 2015; Gantois et al., 2022; Sansone et al., 2019) and subjective perceptual (Camacho et al., 2020; Díaz-García et al., 2023; Dobbin et al., 2021; Garcia-Calvo et al., 2021; Ponce-Bordón et al., 2022) responses, as well as emotional experiences (Kent et al., 2021; Low et al., 2023; Maloney et al., 2022; van Rens et al., 2020).

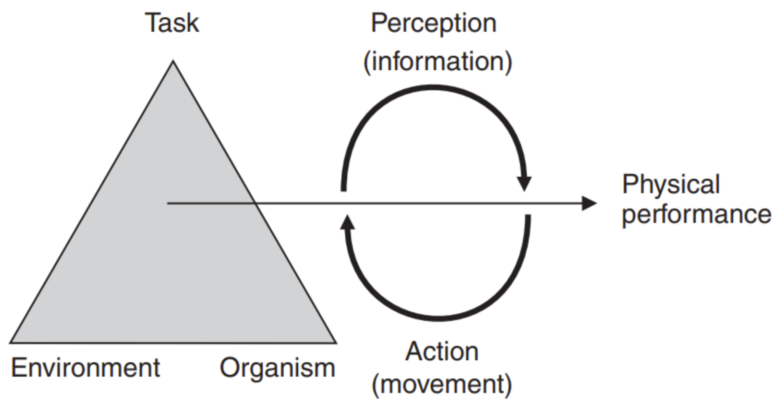

Figure 1.5. Adapted model of Newell's model of interacting constraints. From "Movement Systems as Dynamical Systems," by K. Davids, P. Glazier, D. Araújo, and R. Bartlett, 2003, Sports Medicine, 33(4): p. 247 (https://doi.org/10.2165/00007256-200333040-00001). Copyright 2012 by Springer Nature. Reprinted with permission.

The literature also boasts many examples of applying CLA specifically for sport training purposes, such as in rugby (McKay et al., 2021), soccer (D'Isanto et al., 2021; Práxedes et al., 2019), Australian football (Woods et al., 2019), volleyball (Fernandez-Echeverria et al., 2023), American football (Yearby et al., 2022), and mixed martial arts (Yearby et al., 2024). Though CLA has its roots in ecological dynamics, it is being increasingly recognized in the academic literature that it can also be used beyond the confines of a strict ecological approach to coaching and talent development. Ramos et al. (2021) detailed an action-research intervention in which CLA as well as traditionally-opposed methods (in their case, Step-Game Approach, which takes a constructivist perspective on learning) were both used to develop a female youth volleyball team's tactical knowledge and behaviour. The authors emphasized that combining principles from typically conflicting theoretical frameworks allowed them to satisfy the learning needs of the players, and they also reinforced the importance of regular exposure to representative practices to translate gains in tactical knowledge into functional tactical behaviour (Ramos et al., 2022). Recently, Lindsay and Spittle (2024), too, noted the overlap in CLA and traditional representation-based approaches to motor learning, such as the nonlinearity of learning, the importance of movement variability, and progressing to representative (in terms of both demands and information sources) activities at practice. Effective coaching will integrate strategies, adapting to their athletes' stage of learning, rather than steadfastly practice within rigid theoretical boundaries (Lindsay & Spittle, 2024).

Indeed, there is evidence to suggest that decision making on the field may not be fully understood from an ecological dynamics perspective, which rejects the role of internal representations. Advanced information about a probable outcome enhanced soccer players' ability to anticipate accurately, with the authors suggesting that athletes integrate prior contextual information with live environmental information (Broadbent et al., 2019). Furthermore, Levi and Jackson (2018), through interviews with male professional academy soccer players, identified dynamic and static contextual factors that influence players' on-field decision making. Dynamic themes were related to the situational development of the match, such as perceptions of performance, score, momentum, and coach interactions; while static themes were factors consistent throughout the game, such as match importance, personal pressure, and representative preparation (Levi & Jackson, 2018). Collins et al. (2022) extended upon these findings in their own interviews with male professional rugby players, identifying contextual priors that are considered and treated cognitively to "prime" decision making in the game. Players also described situations in which they think and plan during skill execution. Without dismissing the potential role of ecological approaches, the authors suggest there is a role for more cognitively-focused methods when seeking to develop decision making (Collins et al., 2022). Considering published results such as these, as well as their own experience as practitioners working in high performance sport, members of the same research group have subsequently more explicitly debated the application of, or the strict adherence to, one single theoretical perspective (Bobrownicki et al., 2023). In a response to Yearby et al. (2022), an article in which the authors argued for a "purer" ecological application of CLA within American football with the elimination of practices associated with cognitive approaches, Bobrownicki et al. (2023) detailed the broader context of American football (which applies to other strategic sports) with its multiple phases of planning all the way through to on-field play. They described how direct perception and self-organization may indeed be used to support aspects of match play, but that cognition and internal representation remain very much present and relevant during the extensive development of team-specific game plans, shared mental models, and opponent preparation, and even during real-time play (Bobrownicki et al., 2023). They, along with Lindsay and Spittle (2024) and Ramos et al. (2022), highlight that the integration of theoretical approaches may represent a powerful and effective strategy for coaches. In this way, CLA, in the sense of manipulating constraints with intention, becomes a tool that coaches can use within a broader, eclectic approach (i.e., not limited to the principles of ecological dynamics) (Bobrownicki et al., 2023; Lindsay & Spittle, 2024; Ramos et al., 2022). Underpinning this is an acknowledgement of the need to consider the realities of the sport as well as the specific needs and stage of learning of the team. Indeed, having high-potential ideas of how to enhance or develop the resilience of match-play decision making via more representative training is only one part of the picture. There must also be practical consideration of how to introduce and implement such approaches, as a researcher, within a team.

1.6 Integrated knowledge translation

Sports science is not unique as a domain in which there is still a gap between knowledge generation and application of research into practice (Bartlett & Drust, 2021; Brocherie & Beard, 2020; Fullagar et al., 2019; Leggat et al., 2021; Ross et al., 2018).

The Canadian Institutes of Health Research (CIHR) describes knowledge translation as

> a dynamic and iterative process that includes the synthesis, dissemination, exchange, and ethically sound application of knowledge to improve the health of Canadians, provide more effective health services and products and strengthen the health care system. This process takes place within a complex system of interactions between researchers and knowledge users which may vary in intensity, complexity, and level of engagement depending on the nature of the research and the findings as well as the needs of the particular knowledge user (2016).

Like in many other disciplines, barriers to the translation of knowledge include research conducted that is not relevant, a lack of understanding of the knowledge users/stakeholders, and/or research not suited for an applied context (Finch, 2011; Reade et al., 2008). If knowledge cannot be tailored to the specific needs of a sport organization or team, this can impede their engagement with research (Reade et al., 2008). In line with this, it has been suggested that quality knowledge translation in sport relies on evidence-based practice, i.e., the integration and application of information sourced from athletes, practitioners (including coaches), and academic publications (Bartlett & Drust, 2021; Coutts, 2017). Others also point to the lack of integration of empirical evidence and experiential knowledge as a significant contributor to the gap between generating and applying knowledge (Ross et al., 2018; Woods et al., 2021). Despite the importance and potential of evidence-based practice, these remain considerable hurdles to the integration of theory into practice.

In high-performance sport, coaches play a determining role in initiating and influencing the behaviour change associated with the integration of research findings (Fullagar et al., 2019). However, these high-pressure contexts favour conditions that may compound typical barriers to scientific knowledge engagement. Time pressure, limited resources, prior commitment to or investment in certain approaches, and loss aversion (Tversky & Kahneman, 1991) can contribute to status quo bias, whereby people have an increased propensity to stick with a default option and avoid enacting change even if it is the suboptimal alternative (Samuelson & Zeckhauser, 1988). Application of new knowledge that requires change to established practices may be perceived as threatening safe and reliable methods, questioning staff expertise, and may reduce feelings of control. An important question is therefore how to ensure research findings are relevant and sport- or context-specific, but also how to overcome resistance to change related to implementing them (Ross et al., 2018). This becomes even more pertinent in the context of the current theme, representative training, and the landscape of high-performance sport. With few sport organizations employing skill acquisition experts (Otte et al., 2024; Williams & Hodges, 2023), the individuals tasked with applying research that concerns an area typically dictated by the coach are often "outsider" scientists.

A promising method is integrated knowledge translation (iKT), which can be distinguished from end-of-project knowledge translation (Straus et al., 2013). iKT can be considered as a type of co-production in research (Smith et al., 2022) that involves

> active collaboration between researchers and research users in all parts of the research process, including the shaping of the research questions, decisions about the methods, involvement in the data collection and tools development, interpretation of the findings and dissemination and implementation of the research results (Graham & Tetroe, 2007, p. 21).

The expertise and experience of knowledge users, i.e., those who are "likely able to use the knowledge generated throughout research to make informed decisions about health policies, programs and/or practices" (Canadian Institutes of Health Research, 2016), is valued, with knowledge in iKT sourced from both research evidence and practice/lived experience (Leggat et al., 2021). Originating from within healthcare, iKT is relevant for sport and exercise research: its collaborative nature engages knowledge users from the start and can result in superior methodological feasibility as well as more relevant findings that can be more readily applied in practice (Leggat et al., 2021). Research problems are sourced from knowledge users and multiple methods may be employed to understand the different perspectives – though as a process, iKT remains iterative and adaptable based on evolving priorities, resources, and contexts (Leggat et al., 2021).

The principles of iKT are congruent with findings and recommendations emerging specifically from the area of sport performance. With staff buy-in as a fundamental barrier to research collaboration in team sports (Malone et al., 2019), it is recommended that research questions originate from key stakeholders within the sporting organization (e.g., coaches) with subsequent planning of a research strategy with researchers (Fullagar et al., 2019). Bartlett and Drust (2021) outlined a framework for knowledge translation and performance delivery in sport, identifying key components as evidence-based practice, philosophy, recipients, and facilitation. As described earlier, evidence-based practice emphasizes the value of combining empirical and experiential knowledge (Bartlett & Drust, 2021; Coutts, 2017; Greenwood et al., 2012). Broadly, "philosophy" includes character, leadership approach and evaluation, and represents how the sport scientist engages in their work and is viewed by peers (Bartlett & Drust, 2021). The "recipient" element reflects the need to understand, know, and connect with the stakeholders (e.g., athletes and staff); and "facilitation", or enabling knowledge transfer, is underpinned by the facilitator's skills and attributes, technical knowledge, and interpersonal skills (Bartlett & Drust, 2021). In summary, overall, there appears to be converging support for the close collaboration with research end users during all stages, the selection of context-specific and -relevant questions, the fostering of relationships based on trust and understanding, and engagement and investment by knowledge users – all of which will favour the behaviour change associated with the integration of research on the field. **Therefore, for the fifth project, we aimed to transition from research to action by translating knowledge, gained throughout our earlier work and from the literature, to the field. Our specific objective was to collaborate with Water Polo Canada coaches, athletes, and support staff to develop and integrate more representative training to promote the development of resilient decision making. We hypothesized that involving the key stakeholders throughout the process would result in training designs that would be context-relevant and that would be used in complement to the team's regular practice plans.**

1.7 Summary of research objectives and hypotheses

We first addressed the gap in understanding of athletes' decision-making during exercise. Given the absence of a standardized format for video-based decision-making tests, in our first experimental study, we sought to create one for water polo and assess its construct validity and test-retest reliability. We hypothesized that among female and male water polo players, the test would be able to discriminate according to playing caliber, and that performance would be similar when the test was repeated.

Subsequently, in our second experimental study, we investigated performance on the water polo video-based test during different exercise conditions, also including a domain-general cognitive task in the study design to generate greater understanding of the nature of the exercise-cognition relationship among athletes. The main objective was to examine the effects of exercise intensity and modality on cognitive performance, and we expected that cognitive task performance would be impaired at high intensities for the domain-general Stroop task but not for the domain-specific video-based task.

Fatigue is inherent to competitive match play, but though it is widely perceived to be a disruptor of decision-making performance, the literature presents a hazier picture. Therefore, we aimed to conduct a scoping review to synthesize i) the methods used to induce and attest to the presence of fatigue; and ii) the methods used to assess perceptual-cognitive performance, which underlies match-play decision making. Another aim was to iii) describe what is known about the effects of fatigue on perceptual-cognitive performance among open-skill sports athletes.

In a shift from the laboratory to the field, and to more specifically target the link between match-related fatigue and decision-making performance, in our fourth project, we aimed to evaluate decision making during real competition matches and examine if the hazard of decision-making errors increases as the match and as the tournament progress. On the basis that fatigue develops over the course of a match and accumulates during a tournament, we hypothesized that the hazard associated with making a poor decision would increase over time.

Finally, in our fifth project, the objective was to apply what we learned from our previous studies, combined with extensive supporting evidence in the literature, to integrate more representative training and develop the resilience of match-play decision making among an elite water polo team. We expected that an approach the emphasized collaboration and the contribution of athletes, coaches, and support staff would result in high-quality, context-relevant output that would be integrated within the team's training.

CHAPTER 2

QUESTIONING THE VALIDITY AND RELIABILITY OF USING A VIDEO-BASED TEST TO ASSESS DECISION MAKING AMONG FEMALE AND MALE WATER POLO PLAYERS

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2.1 Abstract

This study aimed to evaluate the validity and reliability of a water polo video-based test to assess decision making. Ninety-five female and male elite/tier 4 (T4) or highly trained/tier 3 (T3) athletes participated using their smartphones. Males repeated the test one week later for reliability analyses. Coaches assessed males' in-water decision making and females were noted as selected or non-selected for the national team. Though response accuracy was significantly different between T3 and T4 athletes (p<0.001) and correlated to age ($r_s(88)=0.43$), sex-specific analyses identified that the only significant differences in accuracy were between T3 females and the other three groups (T4 females, T3 males, T4 males). There was no correlation between males' accuracy and coach-rated decision-making skill, and no difference in accuracy between selected and non-selected females. Reliability analyses comparing performance between weeks revealed an ICC of 0.75, a standard error of measurement of 3.41%, and a significant improvement from week 1 to week 2 among T4 males (p=0.018). Despite associations between accuracy and age, the test was not able to distinguish between more similar groups of athletes. Considering the non-representative design of the test, the construct assessed was declarative game knowledge rather than decision-making skill, with the results suggesting that the former is not critical for evaluating elite players. The performance improvement between weeks among T4 males reinforces that video-based designs should be used cautiously in high-performance sport. However, there may still be practical applications for video-based designs, such as in video review sessions or as a pedagogical tool.

Keywords: game knowledge; tactics; perceptual-cognitive; expertise; athletes; decision making

2.2 Introduction

Water polo is a highly physical and tactical team sport. Players must demonstrate impressive fitness to execute explosive, high-intensity actions and to sustain these efforts throughout a match. Importantly, as in other team sports, physical prowess alone is not enough: expert performance also relies on skillful decision making (Dicks et al., 2019). The evaluation of decision making is complex and is an endeavour that is continuously being pursued by coaches, practitioners, and researchers. In controlled settings, video-based tests are a common method used to assess decision making (Fadde & Zaichkowsky, 2018). These often involve a game clip that is frozen or occluded at a critical point, requiring the participant to respond based on what the next action should be. However, because video-based tests can vary in their degree of representativeness of on-field decision making (Travassos et al., 2013) based on attributes such as the test delivery method (e.g., the equipment used) and the responses required by the participant, it is essential to confirm that the test in question demonstrates sufficient construct validity before implementing it in high-performance sport settings. Otherwise, it would be inappropriate to conclude that participants' performance on the test accurately portrays their decision-making skill – an assumption that can be problematic if untrue if the test is intended for use in talent identification or other assessments.

Construct validity describes the extent to which a test reflects an attribute or skill that cannot be assessed directly, but that is thought to underly performance on the test (Cronbach & Meehl, 1955). It can be evaluated by comparing two groups whom we believe should have different levels of the skill, such as higher- and lower-level athletes (Currell & Jeukendrup, 2008), or by examining the association between test performance and other measures believed to be related to the same construct (Cronbach & Meehl, 1955). Sport science researchers investigating video-based tests have often employed the former method, demonstrating that video-based tests distinguish between groups of athletes divided by playing caliber (Lorains et al., 2013a; Murr et al., 2021; Natsuhara et al., 2020; Rosch et al., 2021; Vaeyens et al., 2007), age (Murr et al., 2021), playing time (Murr et al., 2021), accumulated training hours (Machado & Teoldo da Costa, 2020), and team selection (Murr et al., 2021; Woods et al., 2016). Video-based test results have also been associated with on-field performance (Rosch et al., 2021). Interestingly, though, most of the differences found between caliber groups involved comparisons between high-level athletes and novice or control groups. In contrast, performance on video-based tests was not significantly different between groups when participants were of more similar playing caliber, e.g., elite versus sub-elite (Bennett et al., 2019; Breed et al., 2018; Lorains et al., 2013a), challenging the validity of such tests among more homogenous groups. The representativeness of video-based tests also affects the magnitude of performance differences between athletes of different calibers (Travassos et al., 2013), highlighting that results from one study cannot be generalized to another and supporting the need to independently examine construct validity.

A second crucial metrological parameter to verify is reliability, which describes the extent to which a test provides consistent results when it is performed under similar conditions across more than one testing session (Weir, 2005). Test-retest reliability can be categorized as absolute: reflecting variability within individuals; or relative: quantifying how consistent the test is in ranking individuals within a group (Weir, 2005). Reliability is critical if the test is to be used to quantify the acute or chronic effects of a manipulated variable, such as a training program, exercise intensity, or fatigue, on performance, such as a training program, exercise intensity, or fatigue. Without confirming the reliability of a test, we cannot be confident that differences in performance are attributable to the variable of interest and not simply to the test's inherent variability. Consequently, for us to be able to draw meaning from test results, be it for comparisons between individuals or within individuals over time, it is also crucial to verify the test-retest reliability for each new test. Thus, the objective of this study was to assess the construct validity and test-retest reliability of a water polo video-based test to assess decision making among female and male players. We hypothesized that the test would be able to discriminate between players based on their caliber, and that performance would be similar when the test was repeated.

2.3 Methods

2.3.1 Participants

Ninety-five water polo players (62 female, 33 male) participated in this study and were grouped by sex and caliber. Participants were classified as highly-trained (tier 3; T3) or elite (tier 4; T4) athletes based on their current training status (McKay et al., 2022). The CERPÉ plurifacultaire of the Université du Québec à Montréal approved the secondary use of data and all included participants provided informed consent in that regard.

2.3.2 Decision-making videos

Two coaches, who had a combined 35 years of national team coaching experience, selected 98 game situations from international games played by the Senior Women's National Team. The clips ranged from 3.9 to 13.6 seconds, were all filmed from a third-person perspective (side view), and depicted offensive plays: either 6 vs. 6 or 6 vs. 5 (powerplay). All clips were edited (Adobe Premiere Pro 2020, San Jose, USA) to freeze for one second on the first frame, with a red circle identifying the player who would have possession of the ball at the end of the clip. Imagining themselves as that player, participants were asked to make the best decision possible. In order to add key contextual information to the situations (Runswick et al., 2018), score, game quarter, the time left in the quarter, and shot clock time at the start of the clip were displayed on a black background for four seconds before the start of the game clip. On the final frame, numbers were superimposed to label the teammates, and each video was frozen for five seconds, during which time participants responded. Response options were to shoot, move (i.e., keep possession of the ball and move in), or pass. The pass option also required identifying which of the five teammates the pass would go to. Therefore, in total, there were seven possible responses for each video. Based on consensus, the coaches assigned a value of 0, 1, or 2 to each of the response options, for undesirable, acceptable, and desirable decisions, respectively. It was possible for videos to have more than one "acceptable" or "desirable" decision. During the testing sessions, one coach reviewed the videos and confirmed their assigned ratings of the response options for every video.

2.3.3 Experimental design

The protocol was developed for implementation within the time and budgetary constraints of national team selection camps. The study was first conducted during a Senior Men's National Team camp, where the males viewed 45 videos during one session (1A) and 48 more during a second session (1B) two days later. The videos were presented in sets of 11 or 12 with at least 90 s of break between each set. To assess the reliability of the video-based test, male participants repeated both sessions under the same conditions seven days later. The videos for these third (2A) and fourth (2B) sessions were identical to those shown in 1A and 1B, respectively, though the order of presentation differed: while the order of the sets remained the same, the order of the 11 or 12 videos within each set was randomized to reduce the risk of a practice effect. Due to scheduling constraints, when the females participated during their own Senior National Team camp four months later, they only completed session 1A.

2.3.4 Procedure

Real-world feasibility was an important consideration in the design of this assessment, particularly because it took place during national team selection camps with tight schedules, budget limitations, and large groups of athletes who would need to be tested simultaneously. The videos were projected on a screen, and participants connected with their smartphones to a gamified online quiz application (Ahaslides, Singapore), where each video was a quiz question. Participants were instructed to select from the list of response options displayed on their phones the best decision as quickly as possible, while prioritizing accuracy. Answers submitted after the last frame had been displayed for five seconds were not counted. To promote continued engagement and create additional time pressure, participants received points via Ahaslides that corresponded to both the accuracy and speed of their response, and everyone's scores and rankings were displayed after every set of 11 or 12 videos. Therefore, no video-specific feedback was given about the accuracy of their answers.

There were five familiarization trials during session 1A and three familiarization trials during sessions 1B, 2A, and 2B before participants completed four sets of videos.

2.3.5 Measures

The points tallied in real-time by Ahaslides were used exclusively for task engagement. Participant scores used for analyses were based on the aforementioned coach-assigned values for each response (0, 1, or 2 points). An individual decision-making index (DMI) was calculated for each participant by dividing the points earned by the total possible number of points, multiplied by 100 (Equation 1). For the males, a week DMI was also calculated based on the total points earned for the 93 videos. Thus, all participants had a DMI for 1A, and all males additionally had DMI calculated for week one (1A and 1B performance combined) and week two (2A and 2B performance combined).

$$DMI = \frac{Total\ points\ earned}{2\ points \times number\ of\ videos} \times 100\% \tag{1}$$

After the males' selection camp, the team's head coach subjectively rated the water polo decision making skill of 22 of the male field players from 1-10, where 10 represented the top 10th percentile and 1 represented the bottom 10th percentile of men's senior-level international water polo. After the females' camp, the players' selection status was noted as either non-selected or selected for the Women's National Team talent pool. Selection was based on coaches' perceived potential for the squad for the upcoming Olympics. This difference in how males and females were characterized after their respective camps was based on the large number of females; the fact that the women's team head coach was not familiar enough with many of the players to rate their overall decision-making skill; and the more balanced numbers among the females of who were selected or not.

2.3.6 Statistical analyses

Shapiro-Wilk tests and Levene's tests were used to evaluate the normality and homogeneity of variances, respectively, of the data. When applicable, effects sizes were calculated. For data that were analyzed using parametric tests, Hedges' g_s and Cohen's d_z were used to describe the standardized mean difference of an effect for between-group and within-group comparisons, respectively (Dankel & Loenneke, 2021; Lakens, 2013). Effect sizes were trivial (< 0.20), small (0.20 – 0.49), moderate (0.50 – 0.79), or large (≥ 0.80) (Cohen, 1988).

To estimate the difference between pairs of non-normally distributed groups of data, Cohen's r was calculated as $r = z/\sqrt{N}$, where z is the z value of the Wilcox rank sum test, and N is the sample size.

Cohen's r was interpreted as a small ($0.10 \leq r \leq 0.29$), medium ($0.30 \leq r \leq 0.49$), or large ($r \geq 0.50$) (Coolican, 2013).

2.3.6.1 Participant characteristics

Athletes were compared based on age and years of water polo experience. Independent samples t-tests or Wilcoxon rank sum tests were used to investigate differences between T3 and T4 athletes and between the selected and non-selected females. Kruskal-Wallis tests were used to compare T3 females, T4 females, T3 males, and T4 males, with Dunn's post-hoc pairwise comparisons using Bonferroni-adjusted p-values.

2.3.6.2 Validity

Session 1A DMI scores were compared between T3 and T4 athletes using independent samples t-tests. Spearman's rank-order correlations were calculated between DMI and age and between DMI and years of water polo experience. To investigate possible sex differences, a two-way ANOVA with Sex (female or male) and Caliber (T3 or T4) as factors, followed by Tukey HSD post-hoc tests, was conducted to compared session 1A DMI between T3 females, T4 females, T3 males, and T4 males. Among females and males separately, Spearman's rank-order correlations were calculated between DMI and age, and between DMI and years of water polo experience. Among the males, Spearman's rank-order correlation was also calculated between session 1A DMI and subjective coach decision-making rating. For the females, a Wilcoxon rank-sum test was used to compare the selected and non-selected groups' 1A DMI. Correlations were considered weak ($0.1 \leq r_s \leq 0.39$), moderate ($0.4 \leq r_s \leq 0.69$), or strong ($0.7 \leq r_s \leq 0.99$) (Dancey & Reidy, 2007).

2.3.6.3 Test-retest reliability

Among the males, a paired samples t-test was used to compare week 1 and week 2 DMI. The intraclass correlation coefficient (ICC; 2, 1) was calculated to estimate relative reliability, with reliability considered as moderate ($0.50 \leq ICC \leq 0.69$), high ($0.70 \leq ICC \leq 0.89$), or very high ($ICC \geq 0.90$) (Munro, 2005). The standard error of the measurement ($SEm = \sqrt{MS_E}$, where MSE_E is the mean-squared error) and the minimum difference to be considered real ($MD = SEm \times 1.96 \times \sqrt{2}$) were calculated as indices of absolute reliability. To assess if performance differences between weeks were similar for T3 and T4 males, a follow-up two-way 2 (week: 1 or 2) × 2 (expertise: T3 or T4) mixed ANOVA was conducted with Bonferroni-corrected post-hoc comparisons of estimated marginal means (EMM).

Statistical analyses were carried out using R 4.1.2 (R Core Team, 2022), and the afex (Singmann et al., 2022), emmeans (Lenth, 2020), effectsize (Ben-Shachar et al., 2020), DescTools (Signorell, 2022), and irr (Gamer & Lemon, 2019) packages, with an alpha level of 0.05.

2.4 Results

For validity analyses, two T3 females, one T4 female, and one T4 male were excluded because of confirmed technical difficulties encountered during session 1A. An additional T4 female with a session 1A DMI identified as an extreme outlier (three times the interquartile range lower than quartile 1) was also believed to have had technical issues and was removed from analyses ("What are outliers in the data?," n.d.). For test-retest reliability calculations, two T3 and two T4 males were excluded because of technical issues during one of their four sessions.

2.4.1 Participants' characteristics

There were large, significant differences in age (W = 140.0, p < 0.001, r = 0.73) and years of experience (t(88) = -4.89, p < 0.001, g = 1.04) between T3 and T4 athletes (Table 2.1). T4 participants were older and had played water polo for more years. Sex-based analyses revealed large, significant between-group differences in age (H(3) = 57.8, p < 0.001). T3 females were younger than T4 females (p < 0.001, r = 0.75), T3 males (p = 0.016, r = 0.58), and T4 males (p < 0.001, r = 0.76). T3 males were younger than T4 males (p = 0.012, r = 0.74). Furthermore, differences between groups for years of water polo experience were moderate to large (H(3) = 23.4, p < 0.001). T3 females had fewer years of experience than T4 males (p < 0.001, r = 0.62), as did T3 males (p = 0.0037, r = 0.64). Finally, among females, the selected group was significantly older (W = 134.0, p < 0.001, r = 0.58) and had more years of experience (W = 184.0, p < 0.001, r = 0.49) than the non-selected group.

Table 2.1. Characteristics of all participants included in analyses for session 1A decision-making index (DMI).Measures are presented as median (interquartile range). Values for the females are shown based on their grouping by caliber, as well as based on their grouping by selection status.

	T3 Males	T4 Males	T3 Females	T4 Females	Non-selected Females	Selected Females
n	17	15	36	22	30	28
Age (years)	19.43 (1.85)	23.72 (2.27)	17.69 (1.34)	21.13 (3.93)	17.73 (2.41)	20.49 (4.05)
Water polo experience (years)	9 (2.00)	14 (3.00)	8 (4.00)	10 (4.00)	7 (3.75)	10 (2.50)
Position						
Attacker	12	8	17	12	15	14
Centre forward	1	2	8	2	5	5
Centre defender	2	2	0	5	2	3
Utility	0	0	5	2	5	2
Goalie	2	3	6	1	3	4

2.4.2 Test validity

2.4.2.1 Full-sample analyses

A large, significant difference in session 1A DMI ($t(88) = -3.78$, $p < 0.001$, $g = 0.80$) was observed between T3 and T4 athletes (Figure 2.1A). The significant positive correlation between 1A DMI and age ($r_s(88) = 0.43$, $p < 0.001$, 95% CI [0.25, 0.59]) and years of water polo experience ($r_s(88) = 0.27$, $p = 0.0087$, 95% CI [0.072, 0.46]) were moderate and weak, respectively (Figure 2.2).

2.4.2.2 Sex-specific analyses

For 1A DMI, there was a significant interaction of sex and caliber ($F(1, 86) = 6.66$, $p = 0.012$) with large between-group differences. Post-hoc tests indicated T3 females had significantly lower scores than T4 females ($p < 0.001$, $g = 1.20$), T3 males ($p < 0.001$, $g = 1.27$), and T4 males ($p < 0.001$, $g = 1.33$) (Figure 2.1B).[2]

[2] An ANCOVA that included age as a covariate yielded identical results.

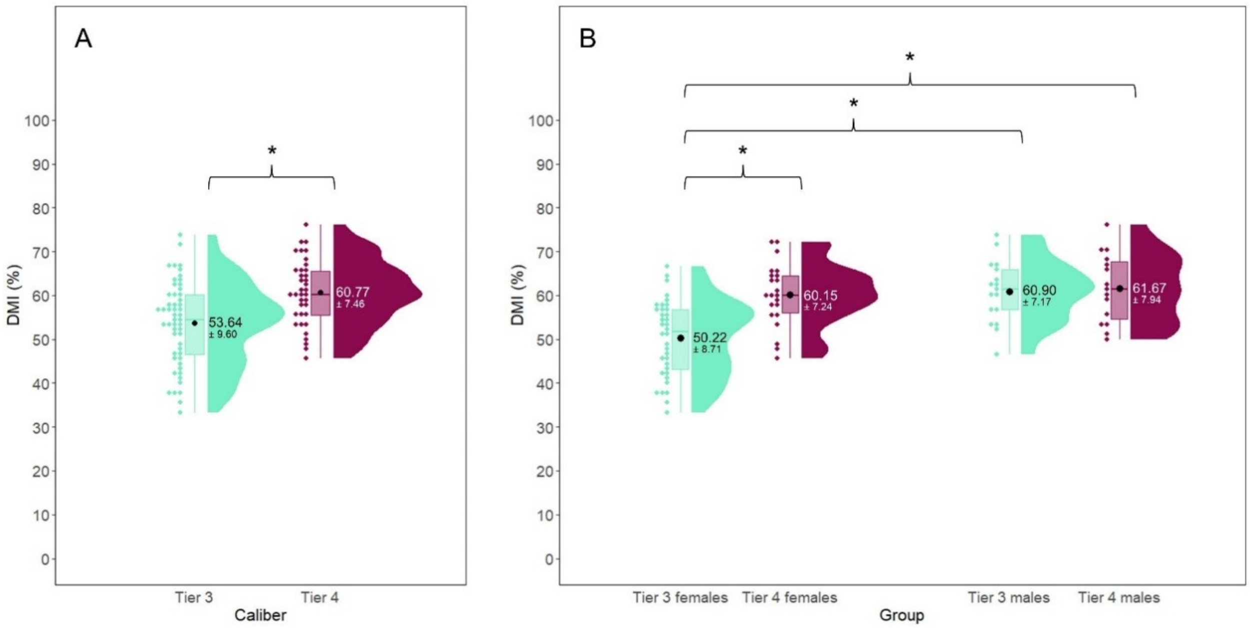

Figure 2.1. Comparison of session 1A decision making (DMI) between groups divided by caliber (A) and by caliber and sex (B). * indicates $p < 0.001$.

Among the females, there were significant positive correlations between 1A DMI and age ($r_s(56) = 0.47$, $p < 0.001$, 95% CI [0.25, 0.65]) and 1A DMI and years of experience ($r_s(56) = 0.28$, $p = 0.031$, 95% CI [0.027, 0.50]) that were moderate and weak, respectively. Among the males, neither age ($r_s(30) = -0.033$, $p = 0.86$, 95% CI [-0.38, 0.32]) nor years of experience ($r_s(30) = -0.062$, $p = 0.74$, 95% CI [-0.40, 0.29]) were correlated with 1A DMI (Figure 2.2). There was also no correlation between males' DMI and the coach ratings of decision-making skill ($r_s(19) = 0.031$, $p = 0.89$, 95% CI [-0.41, 0.46]). When comparing selected and non-selected females, their median 1A DMI scores were 55.00 (interquartile range [IQR] = 13.89) % and 55.56 (15.00) %, respectively, and the difference between the groups was considered small and non-significant (W = 350.0, $p = 0.28$, $r = 0.14$).

2.4.3 Test-retest reliability

When comparing DMI between weeks for all males, there was good relative reliability (ICC = 0.75), but there was a moderate, significant increase in DMI from week 1 to week 2 (t(28) = -2.7, $p = 0.011$, $d = 0.63$). The SEm and MD were 3.41 and 9.44%, respectively. When the males were grouped by caliber, the two-way mixed ANOVA indicated a significant interaction of week and caliber ($F(1, 27) = 7.93$, $p = 0.009$).

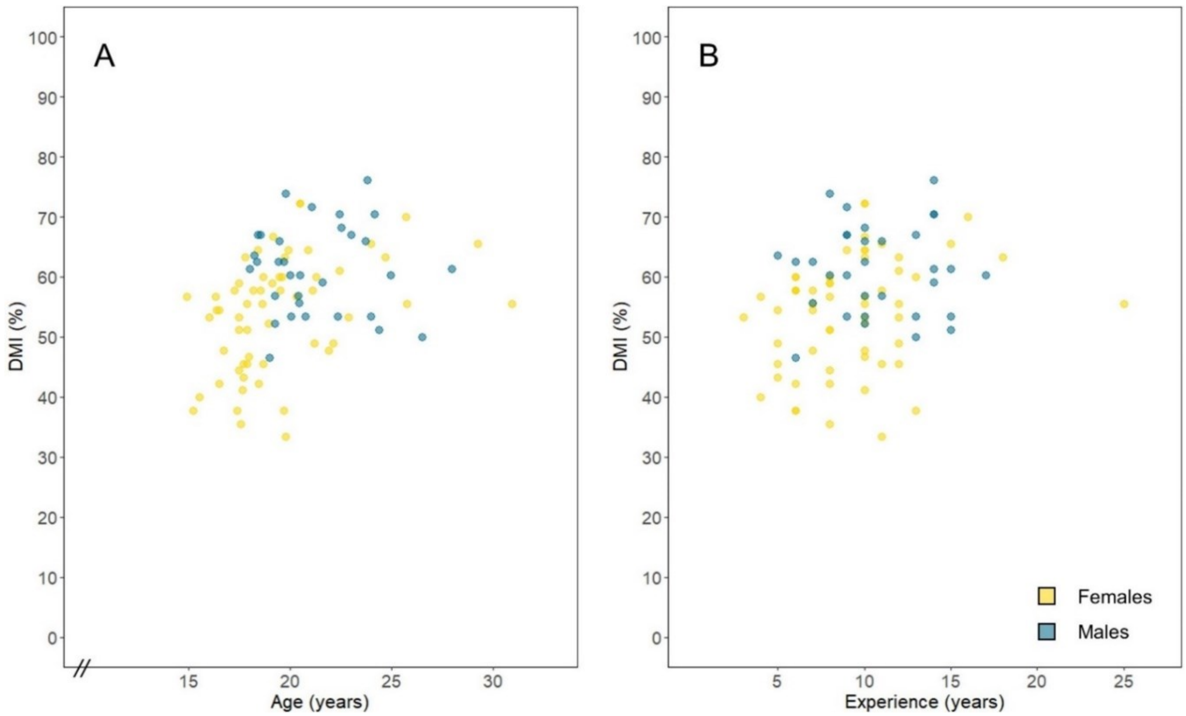

Figure 2.3. The relationship between session 1A decision making index (DMI) and age (A) and experience (B).

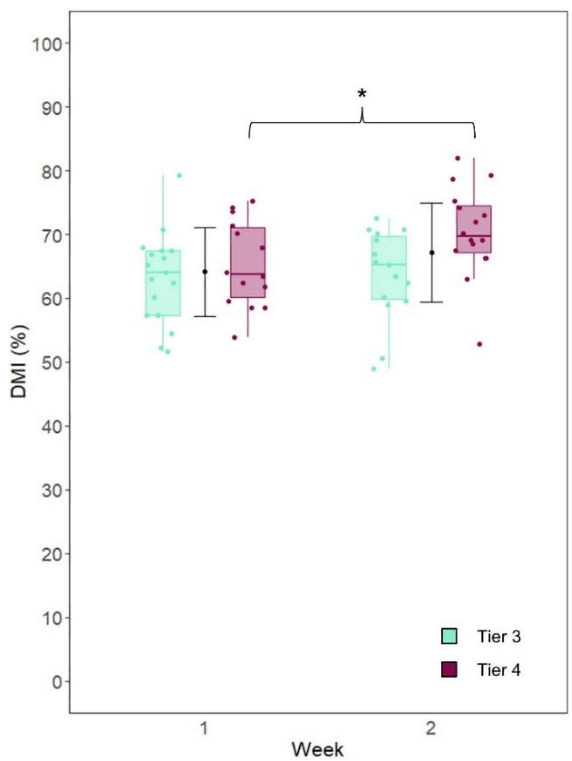

Figure 2.2. Week 1 and week 2 decision making index (DMI) among the males. The mean ± SD for all males is represented by the black point and error bars. To the left and right are the tier 3 and tier 4 participants' scores, respectively. * indicates $p < 0.01$.

Subsequently, post-hoc comparisons revealed that only T4 males had significantly increased their DMI from week 1 (EMM ± SE = 65.3 ± 1.9%, $p = 0.0018$, $d = 1.23$) to week 2 (70.1 ± 1.9%) (Figure 2.3). In contrast, T3 males did not demonstrate a significant improvement from week 1 to 2 (63.4 ± 1.84% vs. 63.7 ± 1.83%, respectively, $d = 0.13$).

2.5 Discussion

This study sought to evaluate the validity and reliability of a video-based test to assess decision making among highly-trained (T3) and elite (T4) female and male water polo players. Our main findings demonstrated that there were differences in accuracy scores between T3 and T4 athletes in the full-sample analysis but not between T3 and T4 males or between females that were and were not selected for the National Team talent pool. Furthermore, the T4 males demonstrated a significant improvement in test performance between weeks. Overall, these results bring into question the construct validity and reliability of the test used in this study for assessing decision-making performance, especially among more homogenous samples of elite athletes.

2.5.1 Validity

When females and males were pooled for analyses, T3 and T4 athletes had significantly different 1A DMI scores, with T4 demonstrating about 13% higher accuracy than T3. However, when the participants were grouped by caliber *and* sex, this difference between calibers was seen only among the female participants. Although both T3 females and males were significantly younger than their T4 counterparts, there was a greater range in age among the females. Furthermore, the T3 females were younger even than T3 males, which may contribute to why only the females retained a significant correlation between age and 1A DMI. In a study using a volleyball-specific decision-making task, De Waelle, Van Bostraeten, et al. (2021) found differences between ages, and further demonstrated that the association between age and decision making was mediated by experience and visual cognition. Not only were the males more similar in age compared to the females, but they were also more homogenous in playing caliber: though also characterized as tier 3, the T3 males could be considered as transitioning to T4. Indeed, half (53%) of the T3 males had international Youth or Junior National Team experience, compared to approximately one-fifth (22%) of the T3 females. Furthermore, more than half (59%) of T3 males continued as part of the National Team program, whereas less than a third (31%) of the T3 females were selected for the National Team talent pool. This finding that the video-based test could not distinguish between groups of more comparable playing level based on accuracy is congruent with previous studies. Accuracy on a soccer video-based test differed between youth academy players and a control group, but not between academy players of different levels (Bennett et al., 2019). For videos played at normal speed, elite and sub-elite Australian football players were more accurate than novices, but there were no differences between the elite and sub-elite groups (Breed et al., 2018). Finally, Australian full-time professional football players on the same team, when grouped by number of games played, also showed no differences in video-based decision-making accuracy (Breed et al., 2018). Although video-based tests have discerned between athletes of more similar caliber, differences were found when the participant response required was a sport-specific motor action (Murr et al., 2021), when videos were played above normal speed (Lorains et al., 2013a), or solely on measures of reaction time (Farahani et al., 2020).

In our study, years of experience consistently showed weak correlations with DMI. In contrast, Machado and Teoldo da Costa (2020) found that a soccer video-based test discriminated between two groups that were formed based on participants' accumulated training hours. Importantly, the differences in training hours were considerable (group means of 2019.0 vs. 95.8 hours) and the group with more training hours was also older (mean age of 16.5 vs. 14.1 years) (Machado & Teoldo da Costa, 2020). In comparison, in the current study, differences in experience and caliber were much less dramatic between T3 and T4 players, and especially among the males. Our results also support the idea that years of participation may be a poor proxy for "experience" or expertise, with many other elements playing critical roles to determine the quality of training or otherwise influence the development of expert performance (Davids & Baker, 2007).

When the females were separated by selection outcome, session 1A DMI was not different between groups, and there was no association between coach ratings of water polo decision making and 1A DMI among the male athletes, further challenging the construct validity of the video-based test to assess decision making in elite athletes. Under multiple frameworks, decision making in sport can be considered as an embodied cognitive process, whereby cognition takes into consideration that we are acting within the constraints of our physical body and in our particular environment (Raab & Araujo, 2019). This approach stresses the bidirectionality of perception and action, the need for representative experimental and practice designs, and the importance of integrating cognitive and motor processes (Raab & Araujo, 2019; Voigt et al., 2023). In the current study, the video-based test took place outside the true sport setting and did not require participants to actually perform the action corresponding to their selected response. It was thus void of the interactions of the players with their environment as well as the coupling between perception and action. Interestingly, youth soccer players that were selected for the national team had better accuracy than non-selected participants on a video-based decision-making test (Murr et al., 2021). While acknowledging that this result applied only to build-up situations (i.e., not to offensive game situations), and that the selected group was less than one-quarter of the size of the non-selected group, it is important to highlight that the test in their study was presented from a first-person perspective and involved a motor response, with participants dribbling the ball and passing when the decision was required (Murr et al., 2021). Indeed, Travassos et al. (2013) found that the magnitude of the effect of expertise on decision making in sport was greatest when the stimulus presentation and the requisite response were representative, reinforcing the importance of including perception-action components that are usually present in athlete-environment interactions. Despite this, other studies on video-based tests that were similarly performed seated and required a passive response (e.g., verbal answer, button press, or pen and paper) have used group differences to support the validity of the test or to conclude that the groups had different levels of sport-specific decision-making (Causer & Ford, 2014; Machado & Teoldo da Costa, 2020; Rosch et al., 2021; Vítor de Assis et al., 2020; Woods et al., 2016). However, performance differences between groups may not necessarily mean the test did indeed measure decision-making skill. This leads to the question of *what* construct is being measured, if not decision making.

On the field, decision making is contextual to the task and depends on an individual's capabilities as well as their interactions with the environment to make embodied choices (Raab & Araujo, 2019). As such, the decision is not "made" until it manifests as a performed action. Watching a video and identifying the appropriate next action does not equate to being able to do it successfully in the context of gameplay, and studies have suggested that it is only the latter that may distinguish superior players among relatively homogenous groups. Indeed, talented high-performance soccer players that were ultimately selected or deselected in a talent development program had similar declarative tactical knowledge (e.g., knowing when to pass to a teammate), but those that were selected had higher scores for offensive procedural knowledge (e.g., being able to get open and in position) (Huijgen et al., 2014). The same result was observed in a similar group of athletes that was divided based on whether they went on to have amateur or professional soccer careers (Kannekens et al., 2011). Therefore, considering the format of delivery and required response of our video-based test, as well as the conceptualization of the performer and the environment characteristics as inherent to the decision-making process, our test was likely an assessment of declarative game knowledge (e.g., knowledge about the game) rather than of water polo in-game tactical decision-making skill (e.g., knowledge of/in the game) (Sullivan et al., 2021). Without diminishing the importance of spontaneous player-environment interactions, it may be relevant to note that water polo is a sport heavily based on tactics, with plays being highly specific to individual teams' systems of play as well as contextually based (e.g., depending on the opposing team). Although declarative game knowledge may be a prerequisite for reaching the highest levels of sport – which is reflected by differences that are frequently reported between novice and expert performers on video-based tests – our results suggest that measuring knowledge about the game might not be useful to distinguish players at the elite level. Players at the highest levels are distinguished more by their in-context individual action capabilities. Accordingly, requiring a sport-specific motor response in reaction to a life-size stimulus viewed from a first-person perspective (e.g., Hinz et al., 2022) and using more immersive stimulus presentation with virtual reality (e.g., Kittel et al., 2019; Pagé et al., 2019; Romeas et al., 2022) are examples of how parameters of a video-based test can be manipulated so that performance would be expected to better reflect decision-making skill, and so that the test may become a tool used to train sport-specific decision making (Pagé et al., 2019; Panchuk et al., 2018; Romeas et al., 2022). Nonetheless, it would still be important to confirm that it is sufficiently sensitive to distinguish between athletes who play/compete at more similar levels before such designs are implemented for talent identification.

2.5.2 Reliability

The high relative reliability (ICC = 0.75) for DMI indicated that the males' performance was consistent relative to one another across both weeks. Notably, though, DMI increased from week 1 to week 2 among T4 males. This result evokes the idea of a testing effect (Schwieren et al., 2017), whereby the test during the first week could have facilitated retrieval of previously learned tactics among the older athletes with more years of game experience (i.e., T4 players) – though this is speculative and would require more evidence to support. Being able to repeat this type of video-based test on multiple occasions, such as to track athletes' declarative knowledge or investigate how response accuracy is influenced by other variables (e.g., fatigue or anxiety), would have been practical. However, the variability that was observed between weeks among elite athletes suggests that caution should be exercised if the same videos are used at more than one timepoint. In general, few studies that use or assess video-based tests report the ICC; of those that do, the ICC ranges from values of 0.29 (Redman et al., 2021) to ≥0.88 (Fortes et al., 2023; Woods et al., 2016), emphasizing the notion that if researchers and practitioners should verify the test-retest reliability of their test within their particular context. Presenting different videos at each measurement could be an option, though it would be important to quantitatively confirm that each separate group of videos is of similar difficulty.

2.5.3 Limitations and strengths

While the inexpensive and user-friendly setup allowed us to accommodate a large group of players participating simultaneously, one limitation was that there was no option to export and thus analyze response time, which may have revealed differences between more homogenous groups. Furthermore, the preparation of videos for the video-based test itself can be a lengthy process that may not be easily integrated within coaches' regular responsibilities. It should be noted that the tactical situations presented in the videos were specifically chosen to be "universal" ones to allow the test to be usable among athletes coming from different teams with different systems of play. Thus, it is possible that the basicness of the tactics reduced the sensitivity of the test to distinguish group differences – though it is worth noting the fact that DMIs were still far from being 100%. Although we recognize the limitations of our study, a strength was the large total sample size of high-caliber participants. Importantly, we included both female and male athletes and conducted sex-based analyses. This contrasts with the vast majority of existing studies in which, consistent with sport and exercise science research overall, female participants are underrepresented (Cowley et al., 2021). Finally, instead of comparing DMI between calibers or age groups only, we also examined its association with coach-rated decision-making skill and selection status. The resultant findings strengthened the notion that the construct validity of video-based tests to assess decision making in elite athletes should be questioned and may differ according to the representatives of the test.

2.5.4 Practical applications

Despite perhaps not measuring decision making skill, passive video-based designs that can accommodate many players at a time, like the one in the current study, may still have practical applications. The number of correct responses for each video ranged widely, from just a few players to all the players selecting the right option. This indicates that, although the expert coaches selected what they believed were basic game situations and the same coaches assigned the correct answers for all the clips, the videos were not equally difficult. This observation, combined with the high level of engagement of the athletes during the sessions, highlight the pedagogical potential of such a tool to help identify gaps in athletes' – and even junior coaches' – knowledge of the team's system of play (Groom & Cushion, 2005). Additionally, this video-based test was low-cost, efficient once videos were cut, and well-received by the athletes. Therefore, it could present a practical way of incorporating more athlete involvement in video sessions that often have low levels of player engagement (Raya-Castellano et al., 2020).

2.5.5 Conclusion

The results of this study question the construct validity and the reliability of a video-based test among elite water polo athletes. When there is a wide range of athletes, it appeared that performance was closely associated with age; however, the test did not distinguish between groups of athletes of more similar caliber. Considering the lack of relationships between accuracy and coach ratings of decision-making skill and with selection status, as well as the non-representative design of the video-based test, the construct being assessed was likely declarative game knowledge (knowledge about the game) rather than decision-making skill (knowledge of/in the game). Furthermore, when repeated, performance on the test was inconsistent between weeks among elite athletes, reinforcing that video-based designs used as evaluations or monitoring solutions should be employed with caution in high-performance sport. Although the validity and reliability of video-based tests may be questioned, there is potential for them to be an engaging pedagogical tool for learning and reviewing team tactics.

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Although the video-based test likely assessed declarative game knowledge rather than water-polo decision-making skill, there was nonetheless interest in investigating cognitive performance during exercise. The format of the video-based test, while a limitation for evaluating decision making, was suitable for a more controlled investigation of the effects of exercise intensity and modality on cognitive task performance. This allowed for the inclusion of a sport-specific task as well as a traditional general cognitive task in our protocol for the following study.

CHAPTER 3

PERFORMANCE ON A DOMAIN-GENERAL AND A DOMAIN-SPECIFIC COGNITIVE TASK DURING EXERCISE: WHAT ARE THE EFFECTS OF EXERCISE INTENSITY, EXERCISE MODALITY, AND TIME OF COGNITIVE ASSESSMENT AMONG HIGHLY-TRAINED ATHLETES?

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3.1 Abstract

This study examined cognitive performance during exercise and the effects of exercise intensity, exercise modality, cognitive task type, and time of assessment, as well as assessed the accompanying self-reported measures. Eighteen highly-trained and elite water polo players (21.04 ± 3.27 years of age; 12 male, 6 female) completed a dual-task protocol on two occasions: once performing a domain-general task (Stroop test with three cognitive trial types) and once performing a domain-specific task (water polo video-based test) during cycling exercise. The exercise involved three work-matched bouts of cycling: continuous moderate intensity, continuous high intensity, and interval high intensity. Self-reported measures (rating of perceived exertion, affect, mental effort, mental and physical demands) were recorded after each exercise condition. There were exercise intensity-related effects on Stroop performance only, including faster reaction time during moderate-intensity exercise for naming trials ($p < 0.001$), and interactions with cognitive trial type ($p = 0.037$). There were no differences between continuous and interval high-intensity exercise conditions for either performance or self-reported responses. Notably, mental effort and demand, in addition to physical effort and demand, were perceived to be significantly higher for the Stroop task than for the video-based test despite identical exercise conditions. Furthermore, Stroop accuracy was associated with more positive affect ($r = 0.47$) and lower ratings of physical demand ($r = -0.37$). These findings imply possible task-specificity of athletes' dual-task performance. They also support the importance of further exploring how task duration and participants' perceptions relate to executive function performance during exercise.

Keywords: Dual task, executive function, decision making, inhibition, water polo

3.2 Introduction

Executive functioning (EF) refers to the family of "top-down" or higher-order mental processes that subserve goal-directed behavior and consist of three core functions: inhibitory control, cognitive flexibility, and working memory (Diamond, 2013). Team sport athletes, such as water polo players, encounter complex tactical situations and self-regulation demands requiring EF (Furley & Wood, 2016; Lazarus, 2000; Montuori et al., 2019). For example, in the highly dynamic context of match play, constantly evolving situations require athletes to suppress ongoing or preplanned responses, e.g., a pass to a teammate, or switch tactical strategies, e.g., from a man-to-man to zone defence. They must also attend to various information sources, e.g., teammates, opponents, referees, the ball, and their own state, integrating this "live" information with coach instructions and team strategy. Naturally then, being able to maintain optimal EF while simultaneously meeting the high-intensity physical demands of match play is crucial to sustaining high levels of performance in the game.

3.2.1 EF at differing exercise intensities

Research among healthy adults performing motor-cognitive dual-tasks points to impaired cognitive performance during high-intensity exercise, and particularly for tasks of EF (Cantelon & Giles, 2021; Labelle et al., 2014; Sudo et al., 2022; Zheng et al., 2021). There is less clarity about athletes' EF performance during high exercise intensities, though. Cardiorespiratory fitness is believed to influence the exercise intensity-cognition relationship (Browne et al., 2017; Chang et al., 2012; Labelle et al., 2013; Lambourne & Tomporowski, 2010). Indeed, Browne et al. (2017) found that, for concurrent exercise and cognitive tasks, participants with high aerobic fitness were largely unaffected by high-intensity exercise for simple cognitive tasks, but the results were equivocal for more complex tasks (e.g., EF tasks). Furthermore, in a review of how physical exertion affects concurrent perceptual-cognitive performance among athletes, it was concluded that moderate- and high-intensity exercise improves speed and does not affect accuracy (Schapschroer, Lemez, et al., 2016). Like in the review by Browne et al. (2017), though, most of the tasks reviewed were attentional tasks or simple/choice reaction-time tasks and did not require EF (Schapschroer, Lemez, et al., 2016). Given that EF could be more vulnerable to high exercise intensities than simpler tasks (Cantelon & Giles, 2021; Lambourne & Tomporowski, 2010), there are still gaps in our knowledge of the effects of exercise intensity on simultaneous EF task performance among athletes.

In studies with athletes that specifically compared different exercise intensities, Fontana et al. (2009) as well as Klatt and Smeeton (2021) used soccer video-based decision-making tasks. They both found that accuracy was no different across rest, moderate, and high intensities, and that response times were faster during moderate and high intensities compared to rest and low-intensity exercise. Maximal intensity was also found to result in decreased response times for soccer decision-making tasks (McMorris & Graydon, 1996; McMorris & Graydon, 1997; Terry McMorris et al., 1999). Since the participants were all soccer players, these soccer-specific tasks can be considered as domain *specific*. However, there remains a dearth of studies using a dual-task design to investigate athletes' EF performance at different exercise intensities on domain-*general* task (i.e., a task unrelated to the sport domain of the participants). Therefore, it is unknown if athletes' apparent ability to resist performance decrements during high-intensity exercise is related to greater cardiorespiratory fitness and/or tolerance of high-intensity exercise, the domain-specificity of the task, or both. When cognitive tasks are performed at rest, athlete expertise is more prominently distinguished for tests that involve sport-specific (i.e., domain-specific) stimuli compared to domain-general stimuli (Kalen et al., 2021). This invites the idea that there could be a similar pattern during exercise, with athlete expertise manifesting as greater resistance to high-intensity exercise-related performance impairments during domain-specific cognitive tasks compared to domain-general cognitive tasks. However, there is little known about athletes' performance on domain-specific and domain-general tasks during simultaneous exercise. Considering the context of match play decision making, more research in this area is crucial.

3.3 Exercise modality and duration

The effects of exercise modality, i.e., constant intensity versus interval exercise, is also relevant considering the nature of team ball sports. Yet, the existing interval exercise literature is focused on pre-post changes (Hsieh et al., 2021) or involves measuring cognitive task performance at rest between the exercise bouts (Dupuy et al., 2018) as opposed to during the physical exertion, which would be the context for sport performance. To date, research on simultaneous cognitive performance during high-intensity interval exercise remains scarce.

Another research gap is related to the duration of exercise, which may have important interactions with intensity (Sudo et al., 2022). A dynamical view of executive functioning during exercise paints EF as first positively impacted by exercise before being impaired as exercise continues and the individual approaches exhaustion (Schmit & Brisswalter, 2020). It would be reasonable to expect the time course of this progression to occur quicker for higher-intensity exercise compared to lower-intensity exercise because exhaustion would be reached earlier during higher-intensity exercise. While researchers have reported decreased EF performance during later compared to earlier stages of exercise (Donnan et al., 2021), few have considered performance at different timepoints in studies comparing exercise intensities.

3.4 Self-reported measures

Finally, studies in the acute exercise-cognition literature often do not report participants' self-reported measures. However, the interoception model for the acute exercise-cognition interaction highlights that psychological factors and individual-specific assessments of perceived costs influence the nature of catecholamine release at severe exercise intensity to ultimately result in either facilitation or impairment of executive functioning (McMorris, 2021). As well, affective responses to exercise derive in part from interoceptive cues (Ekkekakis et al., 2020), and previous studies have demonstrated lower ratings of affect concomitant to increased inhibitory control error rates during heavy and severe exercise (da Silva et al., 2017), as well as differing affect based on exercise modality (Dierkes et al., 2021) or cognitive task complexity (Vera et al., 2018). Together, this justifies the relevance of examining self-reported measures to understand patterns of behavioural performance in dual-task contexts under different exercise conditions and between different tasks (Craig, 2002).

Thus, the main purpose of this study was to examine, using a dual-task protocol, the effects of exercise intensity and modality on cognitive performances during exercise for both a domain-general Stroop task and a domain-specific water polo video-based task. A second objective was to compare self-reported responses between exercise conditions and cognitive tasks. Associations between self-reported responses and cognitive performance were also investigated. Finally, we aimed to explore the temporal dynamics of cognitive performance (i.e., changes related to the duration of the task). Based on the literature described above, it was hypothesized that 1) cognitive task performance would be impaired at high intensities for the Stroop task but not for the video-based task, 2) self-reported responses would differ between the two tasks and would be correlated with cognitive performance, and 3) cognitive performance would be worse during later stages of the task.

3.5 Materials and methods

3.5.1 Participants

Eighteen water polo players (mean age ± SD: 21.04 ± 3.27 years) participated in this study. Of the six females, four were highly-trained (tier 3) and two were elite (tier 4), and all 12 males were highly-trained (tier 3). Participant performance calibre was determined based on training and competition status, using the framework outlined by McKay et al. (2022). The sample size was constrained by resources and availability of athletes, most of whom play abroad in professional or collegiate leagues (Lakens, 2022). Notably, all participants were members of the senior national team training pool, with the study sample size representing approximately 40% of this population and being comparable to those of previous studies with similar designs and/or research questions (Huttermann & Memmert, 2014; Mekari et al., 2015; M. Smith et al., 2016). Participants were healthy and had normal or corrected-to-normal vision. Exclusion criteria included colour-blindness, a history of neurological or psychiatric disorder, or a concussion in the last three months. Ethics approval was obtained from the research ethics committee at the Université du Québec à Montréal, and all participants provided written consent.

3.5.2 Experimental design

Participants completed one familiarization session (~65 min) during which height and body mass were measured with a stadiometer (seca 213, seca, Hamburg, Germany) and electronic scale (Tanita Pro BC-418, Tanita Corporation, Tokyo, Japan), respectively. Information about training and educational background were also collected. Participants then completed a maximal aerobic power (MAP) test on an electromagnetically braked cycle ergometer (Lode Excalibur, Lode B.V., Groningen, The Netherlands) and were familiarized to the two cognitive tasks and to the scales used for self-reported measures. At least two days after, participants completed the first experimental session (~110 min), with the second experimental session scheduled at least seven days later, but no later than 21 days after. For the experimental sessions, using the same cycle ergometer used for the MAP test, participants performed a dual-task protocol which involved either a Stroop task or a water polo video-based test simultaneous to an exercise protocol. One cognitive task was presented in each experimental session, with the order of presentation counterbalanced between participants (Figure 3.1).

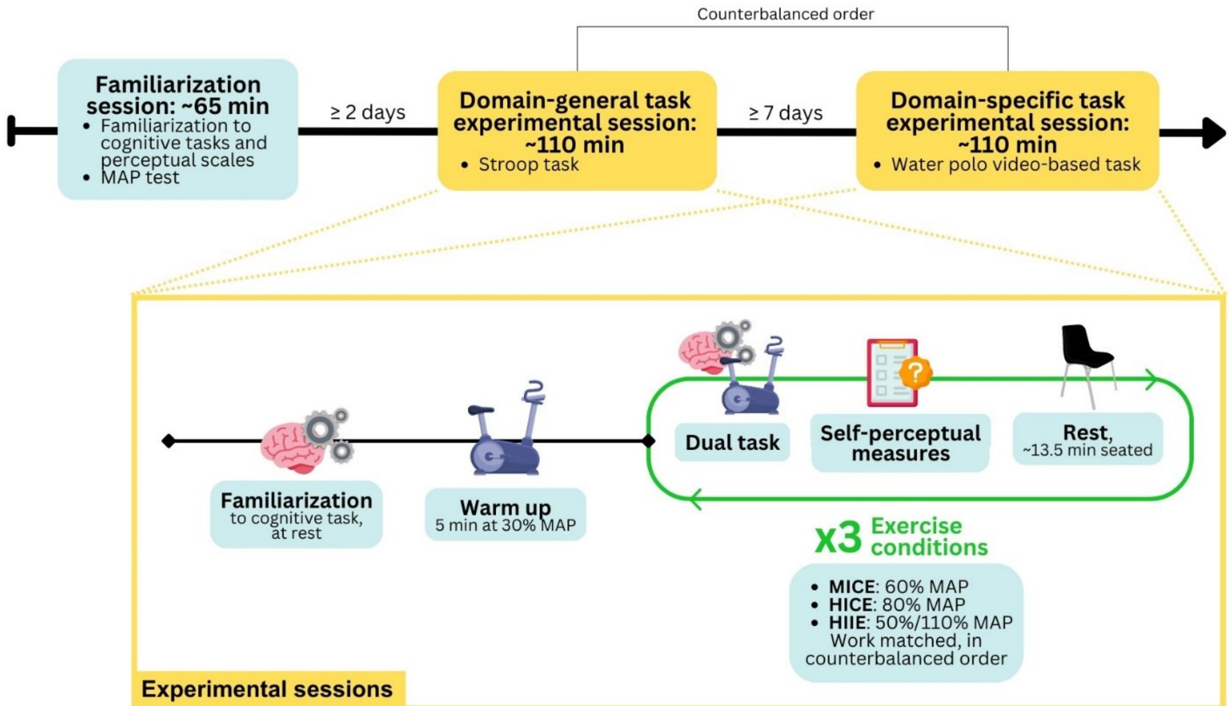

Figure 3.1. Overview of experimental design and procedure. MAP = maximal aerobic power; MICE = moderate-intensity continuous exercise; HICE = high-intensity continuous exercise; HIIE = high-intensity interval exercise.

3.5.3 Maximum aerobic power test

The incremental exercise test began at a workload of 1 W/kg of body mass and increased by 15 W every minute until volitional exhaustion, i.e., until the participant could no longer continue pedalling. MAP was considered as the mechanical power output corresponding to the last completed stage. If the last stage was partially completed, it was still considered to calculate the exact MAP (number of seconds completed/60 sec × 15W + [workload of last fully completed stage]) (Kuipers et al., 1985). Strong verbal encouragement was provided throughout the test.

3.5.4 Dual-task protocol

3.5.4.1 Exercise task

There were three exercise conditions that were counterbalanced between participants according to a 3x3 Latin square design (Labelle et al., 2013; Mekari et al., 2015). Two of the exercise conditions involved continuous exercise: one at moderate intensity (MICE; 60% MAP) and the other at high intensity (HICE; 80% MAP). The third was a high intensity interval exercise condition (HIIE) that required the same average power output as HICE, alternating between 110% MAP and 50% MAP every 14 seconds. The exercise conditions were work matched, with durations of 8 minutes 16 seconds for MICE and 6 minutes 12 seconds for HICE and HIIE. Each exercise condition was preceded by a 15-second ramp-up with the load gradually increasing from 0 W to the target power output. Before the first exercise condition, participants warmed up for five minutes at 30% MAP. Participants were instructed to maintain a consistent self-selected cadence between 60-100 RPM throughout, and at the end of the exercise, had a 60-second active recovery at 30% MAP. This was followed by seated passive recovery for 12.5-14.5 minutes, while they watched an emotionally neutral documentary, before the next exercise condition.

3.5.4.2 Cognitive tasks

Domain-general task: Stroop test. The domain-general task was created using *Expyriment* (Krause & Lindemann, 2014) and was a computerized four-colour Stroop test based on those used by Chaparro et al. (2020); Labelle et al. (2013); Labelle et al. (2014); Mekari et al. (2015). Participants responded by using their thumbs to press one of the four buttons installed on the ergometer handlebars (see Figure 3.7). Each button was associated with one colour (green, yellow, blue, or red), indicated by a sticker of the corresponding colour on the button. To allow for exploration of the temporal dynamics (i.e., changes in performance over time), the dual-task portion of each exercise condition was subdivided into three periods (first, middle, and last), with the cognitive task centred within each period (Figure 3.2). Each of the three periods within each exercise condition consisted of two sets of 20 trials. The first six trials were naming trials, which required participants to identify the font colour of the visual stimulus (XXXX). The remaining 14 trials were executive trials, which included a mix of 10 inhibition trials and four switch trials presented pseudo randomly. In the inhibition trials, participants were instructed to name the colour (GREEN, YELLOW, BLUE, or RED) of colour-words that represented a different colour (e.g., GREEN printed in blue). In the switch trials, a rectangle surrounded the word, indicating to participants that they should instead identify the meaning of the word, ignoring the ink colour. Each stimulus was displayed for 1700 ms, with 300 ms of black screen between stimuli, and was presented in English or French based on the participant's dominant language. Reaction time (RT, in ms) was collected for each trial and accuracy was calculated as (correct answers/total stimuli presented × 100%).

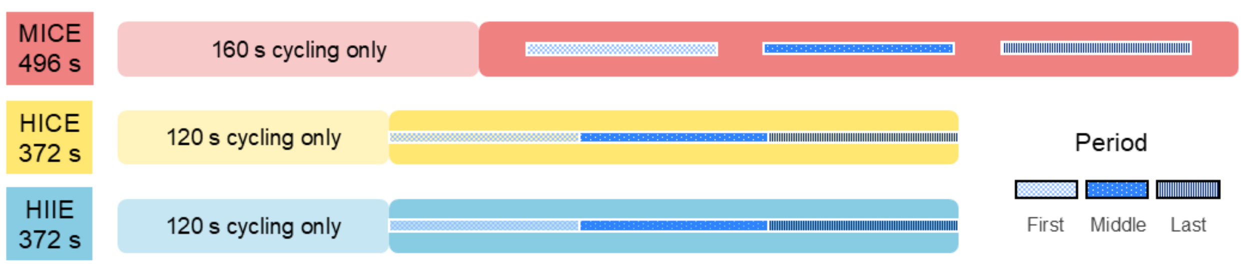

Figure 3.2 The division of the Stroop task into periods for exploratory analyses of temporal dynamics of task performance. The number of trials presented in each period was identical and each period was centered in the corresponding third of the exercise condition within what was considered the dual-task portion.

Domain-specific task: Video-based test. The domain-specific task involved video clips of water polo offensive game situations. The creation and display sequence of the videos is detailed in Dong, Berryman, et al. (2024). Briefly, to provide game context (Runswick et al., 2018), each video started by displaying the score, game time, and shot clock time. Then, a game situation was shown, freezing on the last frame for 2000 ms, at which time participants had to indicate if the player in possession of the ball should shoot, move, or pass. In this study, participants responded verbally with "shoot", "move", or "pass X", where "X" was the numerical position of the teammate who should receive the pass. Participants earned 0, 1, or 2 points for undesirable, acceptable, and desirable decisions, respectively. Failure to respond or to respond within the 2000 ms resulted in 0 points for that video.

Calculated using the data from Dong, Berryman, et al. (2024), the ICC for collective accuracy ([sum of points earned by all participants]/[points if all participants made desirable decisions]), which is a proxy for the video difficulty, was 0.86 (unpublished), suggesting that relative reliability for between-video difficulty was high. The 48 videos with the highest collective accuracy were used in the current study and had a mean duration of 11.2 s. They were divided into four groups of equivalent difficulty, with group means ranging between 79.4% and 79.8% (group standard deviations ranging between 9.1 and 11.0%). One group of 12 videos was associated to each exercise condition, with the videos in each exercise condition presented in a different randomized order for each participant. Participants' answers were recorded by hand for accuracy analyses and verbal response time was recorded using Presentation (Neurobehavioral Systems Inc., Berkeley, CA).

Both cognitive tasks were administered on a 58-inch LCD television positioned about 15 cm in front of the most anterior part of the ergometer. During the familiarization to both tasks, participants were seated on the ergometer. At the familiarization session, after being introduced to the task instructions, participants performed a Stroop task, repeating a series of 22 trials (8 naming, followed by 14 executive) a minimum of six times and until they obtained correct responses for at least 13/14 of the executive trials. They then performed five trials (i.e., videos) of the water polo-specific video-based test twice. For both tasks, participants were instructed to provide the correct response as quickly as possible and did not receive feedback about their responses during the experiment. On the day of the experimental sessions, they repeated the familiarization for the corresponding test, as well as performing a full round of the task, at rest, exactly as it would be presented during the exercise conditions. During the dual task, the cognitive task began after two minutes (HICE and HIIE) or two minutes 40 seconds (MICE) of cycling, such that the period of cycling before the start of the cognitive task was also work-matched.

3.5.4.3 Self-reported measures

Immediately after each exercise condition, participants provided a rating of perceived exertion (RPE) using a Borg CR-10 scale (Borg, 1998) based on the question "how hard was the exercise you just performed?". They were also asked to indicate what their affective valence was during the exercise using the Feeling Scale (Hardy & Rejeski, 1989), to rate the mental and physical demand of the task using the corresponding sub-scales of the National Aeronautics and Space Administration Task Load Index (NASA-TLX; Hart and Staveland (1988)), and to mark a point on a 150 mm Rating Scale of Mental Effort (RSME; Zijlstra (1993)).

3.5.5 Analyses

3.5.5.1 Cognitive task performance

Only RTs of correct answers were considered, with RTs faster than 100 ms being excluded (Schmit et al., 2015). Linear mixed models were conducted for RTs of correct answers for both cognitive tasks, and for accuracy on the video-based test. Fixed factors in the models were Exercise order (first, second, or third), Exercise condition (MICE, HIC, HII), Sex (female, male) – and for Stroop results only, Cognitive trial type (naming, inhibition, switch) and Cognitive trial type * Exercise condition. As an exploratory analysis, an additional model was conducted for the Stroop test with a dynamical perspective of EF during exercise (Schmit & Brisswalter, 2020). It involved the aforementioned fixed factors, and it considered the time of cognitive assessment relative to the start of exercise by the fixed factors Period (first, middle, last) and Period * Exercise condition * Cognitive trial type. Participant was a random factor for all linear mixed models. Stroop accuracy results demonstrated a ceiling effect, and therefore were analysed using non-parametric tests. One Friedman test was conducted per cognitive trial type to compare between exercise conditions.

3.5.5.2 Self-reported perceptual measures

Linear mixed models were conducted for RPE, affect, mental demand, physical demand, and RSME with Exercise order, Exercise condition, Sex, Cognitive task (Stroop, video-based), and Exercise condition * Cognitive task as well as Sex * Exercise condition as fixed factors. Participant was a random factor. As an exploratory procedure, repeated measures correlations (Bakdash & Marusich, 2017) were calculated between each pair of performance and self-reported measures to investigate relationships that may exist. Performance measures included were accuracy and reaction time on Stroop executive trials (i.e., average of inhibition and switch trials) and on the water polo video-based task.

Effects of model fixed factors were interpreted using type III ANOVA tables. Significant effects and interactions were followed-up with Bonferroni-corrected post-hoc pairwise comparisons of estimated marginal means (EMM). When applicable, effects sizes were calculated. For data that were analyzed using parametric tests, Hedges' g_s and Cohen's d_z were used to describe the standardized mean difference of an effect for between-group and within-group comparisons, respectively (Dankel & Loenneke, 2021; Lakens, 2013). Effect sizes were trivial (< 0.20), small (0.20 – 0.49), moderate (0.50 – 0.79), or large (^{3} 0.80) (Cohen, 1988). Spearman correlations were verified and Kendall's *W* was calculated as the effect size for the Friedman tests. Correlations and effect sizes were considered weak ($0.1 \leq r_s < 0.39$), moderate ($0.4 \leq r_s < 0.69$), or strong ($0.7 \leq r_s < 0.99$) (Dancey & Reidy, 2007; Tomczak & Tomczak, 2014). R 4.2.2 (R Core Team, 2022) was used to conduct statistical analyses and create figures. The emmeans (Lenth, 2020), lmerTest (Kuznetsova et al., 2017), and rmcorr (Bakdash & Marusich, 2017) packages, and an alpha level of 0.05 were used.

3.6 Results

One female and one male were unable to complete the water polo video-based test due to injury and illness unrelated to study participation. All 18 participants completed the Stroop task experimental session (Table 3.1).

Table 3.1. Participant characteristics. Values are displayed as mean ± standard deviation [range].

	Females (n = 6)	**Males (n = 12)**
Age (years)	22.9 ± 4.7 [18.5-30.1]	20.1 ± 1.5 [18.1-23.2]
Education (years)	15.3 ± 3.9 [12-21]	13.35 ± 1.3 [12-16]
Absolute maximal aerobic power (W)	230.0 ± 20.3 [201.0-253.5]	310.8 ± 31.5 [266.0-349.0]
Relative maximal aerobic power (W/kg)	3.0 ± 0.3 [2.7-3.6]	3.4 ± 0.7 [2.1-4.6]
Caliber		
Highly-trained	4	12
Elite	2	0
Weekly training (hours)	18.2 ± 3.3 [12-20]	19.1 ± 4.7 [14-30]
Position		
Attacker	2	5
Center	3	2
Goalie	0	3
Utility	1	2

3.6.1 Domain-general task: Stroop test

3.6.1.1 Without a dynamical perspective

Reaction time. There was a significant interaction of Exercise condition * Cognitive trial type ($F[4, 132] = 2.68$, $p = 0.034$) and significant main effects of Cognitive trial type ($F[2, 132] = 225.17$, $p < 0.001$) and Sex ($F[1, 14] = 23.36$, $p < 0.001$). Only RTs of naming trials differed between exercise conditions, with faster performance during MICE compared to both HICE (est. diff. [95% CI] = -77.96 [-128.36, -27.56] ms, $p < 0.001$, $d_z = 1.05$) and HIIE (est. diff. [95% CI] = -79.83 [-130.23, -29.43], $p < 0.001$, $d_z = 1.20$) (Figure 3.3). Naming trials were faster than inhibition (est. diff. [95% CI] = -182.26 [-211.26, -153.25], $p < 0.001$, $d_z = 2.14$) and switch trials (est. diff. [95% CI] = -244.17 [-273.18, -215.16], $p < 0.001$, $d_z = 3.01$). Inhibition trials were faster than switch trials (est. diff. [95% CI] = -61.92 [-90.92, -32.91], $p < 0.001$, $d_z = 0.67$). Lastly, females were significantly faster than males (est. diff. [95% CI] = -140.570 [-202.94, -78.19] ms, $p < 0.001$, $g_s = 1.02$).

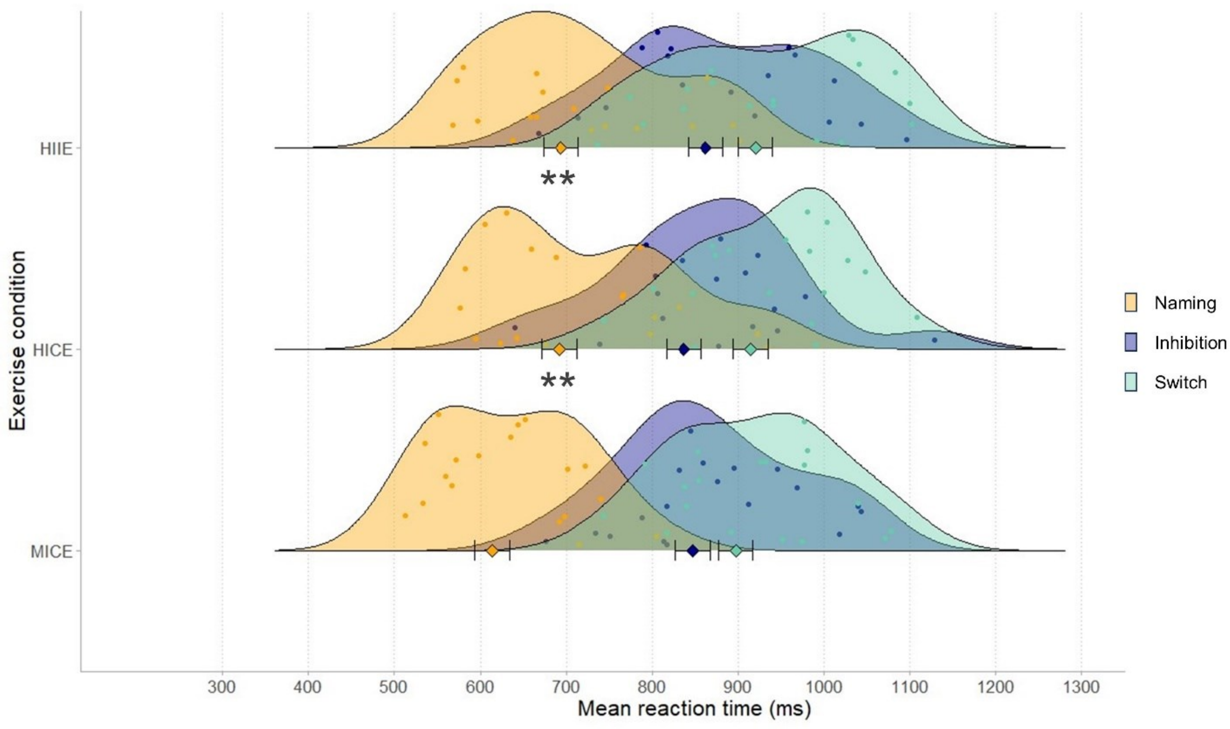

Figure 3.3. Stroop task RT for the different cognitive trial types in each exercise condition. **naming trial RT were significantly slower during HICE and HIIE compared to MICE, p < 0.001.

Accuracy. There were no differences in accuracy between exercise conditions for naming trials ($\boldsymbol{X}^2(2)$ = 2.15, p = 0.341, W = 0.060), inhibition trials ($\boldsymbol{X}^2(2)$ = 2.32, p = 0.314, W = 0.064), and switch trials ($\boldsymbol{X}^2(2)$ = 1.58, p = 0.455, W = 0.044) (Table 3.2).

Table 3.2. Accuracy (%) on the Stroop test as medians [interquartile range] and for the water polo video-based test as means ± standard deviation.

Exercise condition	**Task**			
	Stroop test			**Water polo video-based test**
	Cognitive trial type			
	Naming	*Inhibition*	*Switch*	
MICE	100.00 [4.76]	95.00 [6.25]	93.75 [12.50]	72.92 ± 13.52
HIC	97.62 [8.93]	96.67 [6.67]	95.83 [8.33]	66.67 ± 14.43
HIIE	97.62 [4.17]	93.33 [6.67]	91.67 [7.29]	76.04 ± 12.59

3.6.1.2 With a dynamical perspective

Reaction time. There were significant interactions for Exercise condition * Period (F[4, 440] = 5.63, p < 0.001), Cognitive trial type * Period (F[4, 440] = 2.58, p = 0.037), Exercise condition * Cognitive trial type (F[4, 440] = 4.62, p = 0.001, and significant main effects of Exercise order (F[2, 440] = 5.11, p = 0.006) and Sex(F[1, 16] = 21.97, p < 0.001).

The Exercise condition * Period interaction indicated that, during HICE, there were longer RTs in the middle period compared to the first period (est. diff. [95% CI] = 55.7 [17.86, 93.56] ms, p = 0.001, d_z = 0.51) (Figure 3.4A). A similar observation was found during HIIE with the last period identified as slower than the first (est. diff. [95% CI] = 42.10 [4.25, 79.95] ms, p = 0.023, d_z = 0.41). Thus, there were no differences between exercise conditions in the first period, but RTs were faster during MICE than during both HICE (est. diff. [95% CI] = -72.78 [-110.69, -34.87] ms, p < 0.001, d_z = 0.61) and HIIE (est. diff. [95% CI] = -43.04 ± -80.94, -5.13] ms, p = 0.020, d_z = 0.38) in the middle period, and also faster than HIIE in the last period (est. diff. [95% CI] = -70.94 -108.85, -33.03] ms, p < 0.001, d_z = 0.64).

The Cognitive trial type * Period interaction revealed that switch trial RTs were slower in the last compared to the first period (est. diff. [95% CI] = 41.42 [3.57, 79.27], p = 0.027, d_z = 0.34) (Figure 3.4B).

Inhibition trial RTs were faster than switch trial RTs in the middle (est. diff. [95% CI] = -70.10 -107.94, -32.25] ms, $p < 0.001$, $d_z = 0.62$) and last (est. diff. [95% CI] = -87.96 [-125.81, -50.12] ms, $p < 0.001$, $d_z = 0.65$) periods, but not the first. Regardless of period, naming trial RTs were always faster than both inhibition and switch trial RTs ($p < 0.001$).

The Exercise condition * Cognitive trial type interaction demonstrated that the only differences between exercise conditions were for naming trials, with faster RT during MICE compared to both HICE (est. diff. [95% CI] = -79.77 -117.68, -41.87] ms, $p < 0.001$, $d_z = 0.81$) and HIIE (est. diff. [95% CI] = -79.48 -117.39, -41.58] ms, $p < 0.001$, d_z=0.81) (Figure 3.4C).

For the main effect of Exercise order, participants were slower during the first compared to the second (est. diff. [95% CI] = 25.27 [3.31, 47.22] ms, $p = 0.018$, $d_z = 0.21$) and third (est. diff. [95% CI] = 25.31 [3.35, 47.26] ms, $p = 0.018$, $d_z = 0.24$) exercise conditions performed. Females were significantly faster than males (est. diff. [95% CI] = -138.64 [-201.34, -75.94] ms, $p < 0.001$, $g_s = 0.95$).

3.6.2 Domain-specific task: Video-based test

There were no significant main effects of Exercise order ($F[2, 27.41] = 0.36$, $p = 0.70$), Exercise condition ($F[2, 27.41] = 1.14$, $p = 0.34$) or Sex ($F[1, 14.04] = 0.00076$, $p = 0.98$) (Figure 3.5) on RT. Likewise for accuracy, there were no significant effects of Exercise order ($F[2, 27.61] = 0.10$, $p = 0.91$), Exercise condition ($F[2, 27.61] = 2.29$, $p = 0.12$), or Sex ($F[1, 14.04] = 0.040$, $p = 0.84$) (Table 3.2).

3.6.3 Self-reported perceptual measures

For affect, there was a significant interaction of Sex * Exercise condition ($F[2, 76.67] = 3.96$, $p = 0.023$). Among the females, affect for MICE was rated higher than for HICE (est. diff. [95% CI] = –1.92 [0.50, 3.33] AU, $p = 0.004$, $d_z = 0.88$) and HIIE (est. diff. [95% CI] = 2.38 [0.96, 3.79], $p < 0.001$, d_z=1.06).

There were main effects of Exercise condition and Task for RPE, mental demand, physical demand, and RSME. Briefly, results show that significant differences existed between MICE and HICE and MICE and HIIE, but not between HICE and HIIE. Pairwise comparisons are detailed in Table 3.3. Additionally,

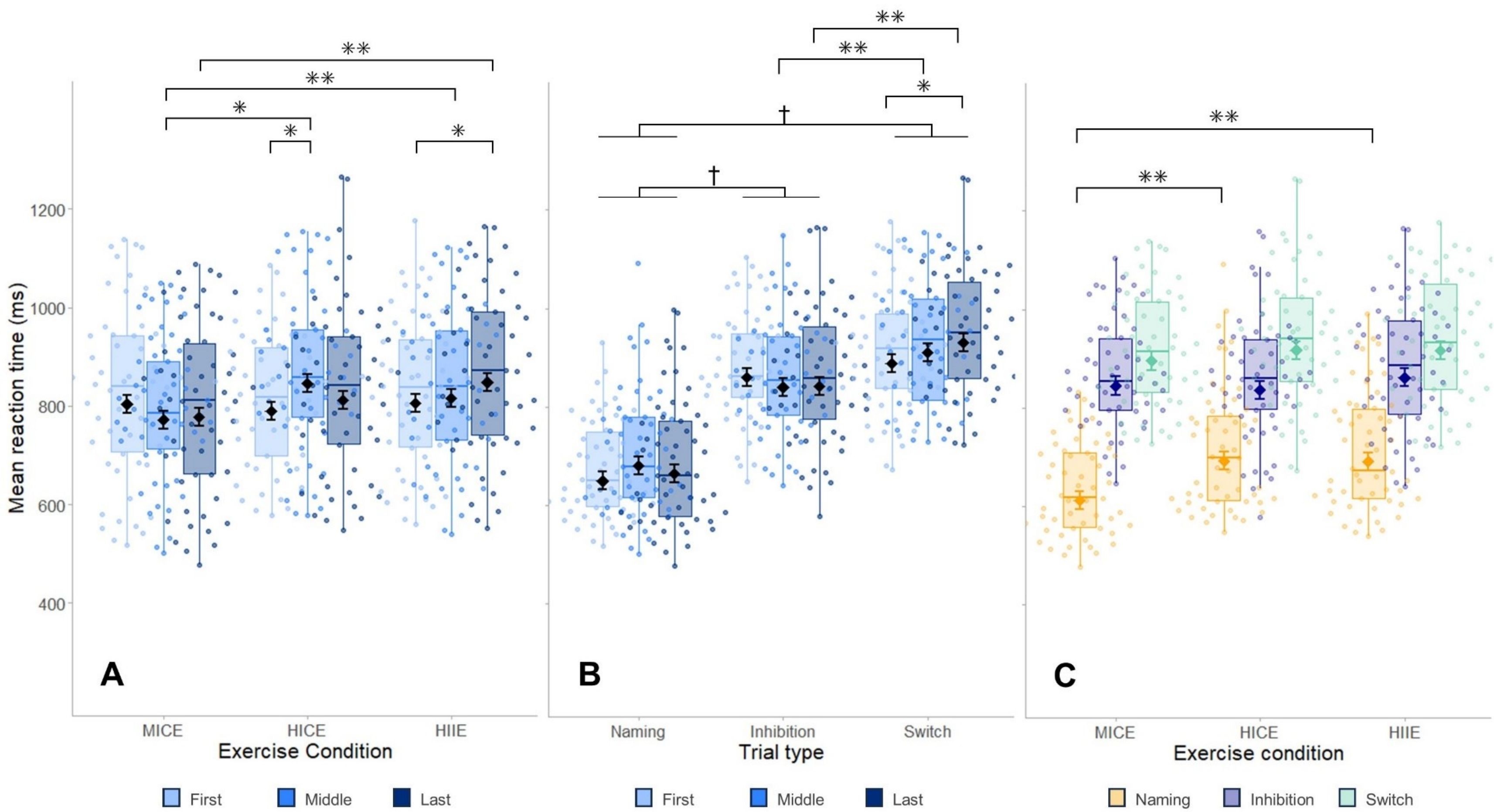

Figure 3.4. Stroop RT for A) different periods in each exercise condition; B) different periods for each cognitive trial type; C) different cognitive trial types in each exercise condition. *Interaction effect, $p < 0.05$; ** Interaction effect, $p < 0.001$; † Main effect, $p < 0.001$.

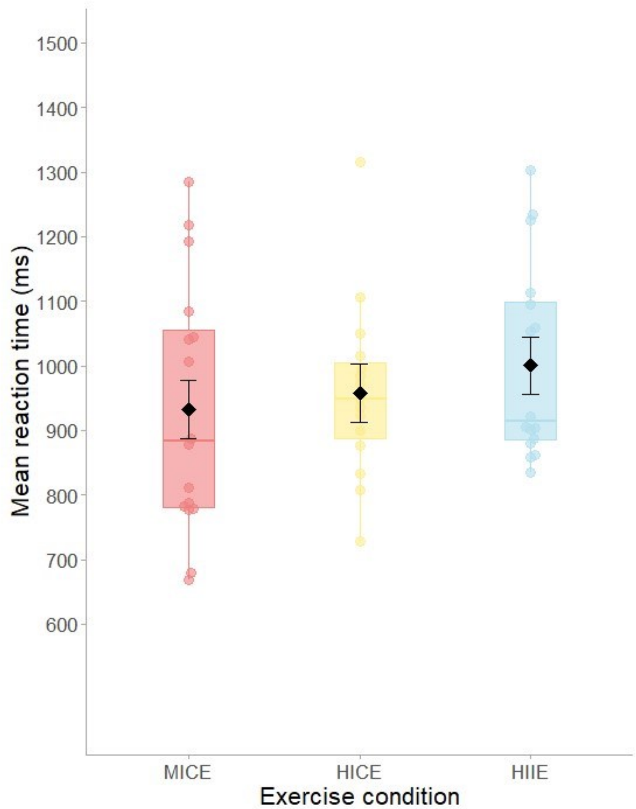

Figure 3.5. Reaction time on the water polo video-based test. There were no significant differences between exercise conditions.

Table 3.3. Pairwise comparisons of the main effects of exercise condition and task on perceptual measures.

	Estimated difference	95% CI	Sig.	Effect size
Exercise condition				
MICE vs HICE				
RPE	-1.85	[-2.58, -1.12]	**< 0.001**	1.22
Physical demand	-12.05	[-19.01, -5.09]	**< 0.001**	0.79
Mental demand	-5.74	[-13.74, 2.27]	0.250	0.18
RSME	-14.37	[-22.34, -6.40]	**< 0.001**	0.90
MICE vs HIIE				
RPE	- 2.03	[-2.76, -1.30]	**< 0.001**	0.99
Physical demand	-15.59	[-22.55, -8.62]	**< 0.001**	0.89
Mental demand	-9.67	[-17.49, -1.86]	**0.016**	0.66
RSME	-16.13	[-24.10, -8.16]	**< 0.001**	0.85
Task				
Stroop vs Water polo video-based test				
RPE	0.57	[0.11, 1.03]	**0.016**	0.44
Physical demand	4.71	[0.31, 9.12]	**0.036**	0.33
Mental demand	9.65	[4.68, 14.61]	**< 0.001**	0.44
RSME	11.73	[6.67, 16.79]	**< 0.001**	0.65

ratings were significantly higher for the Stroop task than for the water polo task. Exercise order had a significant main effect on mental demand (F[2, 74.56] = 3.53, p = 0.034) and on RSME (F[2, 75.33] = 5.14 p = 0.008), with higher mental demand (est. diff. [95% CI] = 7.92 [0.50, 15.34] AU, p = 0.033, d_z = 0.26) and effort (est. diff. [95% CI] = 9.50 [2.04, 16.95] mm, p = 0.008, d_z = 0.34) rated for the first exercise condition compared to the last.

Stroop accuracy was positively correlated with affect ($r(31)$ = 0.47, p = 0.006, 95% CI [0.14, 0.70]) and negatively correlated with ratings of physical demand ($r(31)$ = -0.37, p = 0.033, 95% CI [-0.63, -0.033] (Figure 3.6). There were no significant correlations between any perceptual measures and Stroop RT, nor with accuracy or RT for the water polo video-based test.

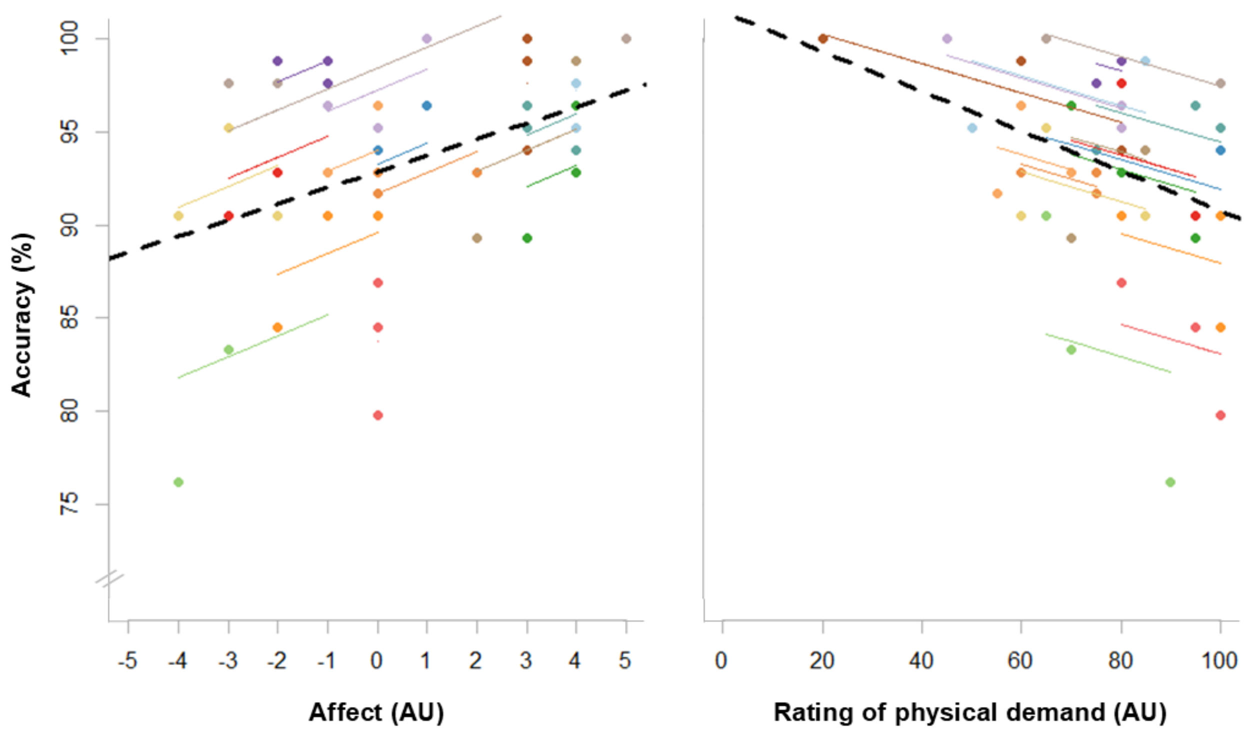

Figure 3.6. Repeated measures correlation of Stroop accuracy on executive (inhibition and switch) trials with affect and physical demand. Each participant is associated with a different colour. Separate parallel lines are fit to the data from each individual and the dashed line represents the overall fit.

3.7 Discussion

This study sought to examine cognitive performance among highly-trained water polo players during exercise in a dual-task protocol. For both a domain-general (i.e., Stroop test) and a domain-specific (i.e., water polo video-based test) cognitive task, an investigation was conducted about how cognitive performance, and the accompanying self-reported responses, are affected by exercise intensity, exercise modality, and the time of cognitive assessment. It was found that there were exercise intensity-related effects on Stroop RT only and that these effects involved interactions with duration and cognitive trial type. Exercise modality did not have any significant effects, with no differences in performance or self-reported responses between HICE and HIIE – perhaps related to the fact that both protocols were work-matched. Interestingly, RSME, mental demand, RPE, and physical demand were rated higher for the Stroop task than for the video-based task – despite an identical physical protocol. Finally, more positive affect and lower perceived physical demand were significantly associated with better Stroop accuracy.

3.7.1 Task performance

For the domain-general Stroop task, there was no simple main effect of exercise condition on executive functioning: inhibition and switch trial RTs were no different between the exercise conditions. This contrasts with existing studies conducted with non-athlete samples, where inhibitory control performance was adversely affected during high-intensity exercise (da Silva et al., 2017; Komiyama et al., 2020; Labelle et al., 2013; Mekari et al., 2015; M. Smith et al., 2016). However, fit individuals are more able to maintain cognitive performance during exercise compared to their lower-fit counterparts (Goenarjo et al., 2020; Labelle et al., 2014), possibly because their habituation to greater metabolic workloads requires fewer resources to be shifted away from regions responsible for cognitive task performance (Audiffren, 2016; Brisswalter et al., 2002). Another possible explanation is that factors related to perception of effort costs, such as experience of similar exercise, a high perception of fitness, and/or a high level of motivation could influence the nature of neurophysiological events (e.g., locus coeruleus-norepinephrine release) and thereby assist in facilitating or preserving cognitive performance during exercise (McMorris, 2021). Athletes may also perceive high-intensity exercise tasks or exercise testing environments as less stressful, which could mean less of an increase in cortisol concentrations due to HPA axis activity – increases that when large enough, can also lead to overarousal and disrupted cognitive performance (Davis et al., 1981; McMorris et al., 2016). For a computerized attentional breadth task that involved detecting form and shading of stimuli, Huttermann and Memmert

(2014) concluded that athletes increased their performance with exercise intensity, while non-athletes exhibited performance that followed an inverted-U shape. In a choice RT test, fencers had shorter RTs during exercise than at rest, with no differences between intensities, while non-fencers demonstrated no differences between rest and any of the exercise conditions. It should be noted that these were non-executive tasks (Huttermann & Memmert, 2014; Mouelhi Guizani et al., 2006) and lower exercise intensities (Huttermann & Memmert, 2014) than those in the present study.

Interestingly, while there were no differences between exercise conditions in the first period, there were significant increases in RT within the HICE and HIIE exercise conditions only. Though on a longer timescale, well-trained team sports players that completed an 80-minute interval cycling dual-task protocol, too, demonstrated decreases in Stroop performance on incongruent (inhibition) trials in the second and third quarter compared to the first (Donnan et al., 2021). The increase in switch RTs found in the present study, from the first to the last period, is also indicative of duration-related effects of exercise, and is coherent with the idea that performance on more complex tasks exhibits higher susceptibility to exercise-related impairment (Browne et al., 2017; Cantelon & Giles, 2021; Chang et al., 2012). These results indicate that highly-trained athletes still do experience exercise intensity-related effects on simultaneous executive functioning, but that there is an important interaction with time of cognitive assessment, thus supporting the need to more specifically investigate the intensity-duration relationship within a dynamical fatigue-based neurocognitive perspective of executive functioning during exercise (Schmit & Brisswalter, 2020).

The lack of differences in Stroop accuracy between exercise conditions, regardless of the cognitive trial type, may be explained by a ceiling effect. Indeed, it has been suggested that performance on tasks like the Stroop test is measured by RT, reflecting processing efficiency, with accuracy measures to keep participants committed to properly performing the task (McMorris & Hale, 2012). There were also no differences in accuracy for the water polo video-based test, although the scores suggest that it was not due to a ceiling effect. In conjunction to this finding, and in contrast to the results from the Stroop task, there were no significant exercise intensity-related differences in RT in the water polo video-based test. Other protocols also revealed no differences or even improved performances at higher intensities for sport-specific decision-making (Fontana et al., 2009; Klatt & Smeeton, 2021) or pattern recall (Schapschroer, Baker, et al., 2016) tasks performed under different exercise conditions. The primary cognitive processes being tested by these tasks may differ from tasks such as a Stroop protocol, and task type/complexity is recognized as affecting the exercise-cognition relationship (Cantelon & Giles, 2021; Lambourne & Tomporowski, 2010; Tempest et al., 2017). Indeed, differences between the two tasks in the current study in how performance was affected by exercise intensity could be associated with the tasks assessing different fundamental cognitive functions (e.g., inhibitory control and cognitive flexibility versus declarative game knowledge and pattern recognition), which may vary in their sensitivity to high-intensity exercise. Another factor that could play a contributing role is the domain-specificity of the task. The "expert performance approach" emphasizes that higher-skilled athletes are distinguished by better performance on sport-specific tasks (Kalen et al., 2021; Mann et al., 2007), and the present results may indicate characteristics of this expertise are also resistant when under high physical loads – which would indeed be how sport-specific tasks are often experienced. Schmaderer et al. (2023) explored potential mechanisms behind this, measuring cerebral cortex oxygenation of soccer players during a domain-general task that required responding to visual and auditory cues (Vienna determination test) and a sport-specific one that required choosing to shoot, pass or dribble the ball based on still images. They found lower cortical activity during the sport-specific task compared to the domain-general task, attributing this to players being more familiar with the sport-specific stimuli and more automatic and/or efficient during domain-specific cognitive tasks. Therefore, it was suggested players were expending less cognitive effort during the sport-specific task than during the domain-general task (Schmaderer et al., 2023). The water polo athletes in the present study would indeed have been more familiar with the format of the game clips in the video-based than with the novel stimuli of the Stroop test. It should be reemphasized that in the current study, as well as in that by Schmaderer et al. (2023), there were differences other than just domain-specificity between the two tasks. The self-reported responses, though, may help understand the differential patterns of performance.

3.7.2 Self-reported measures

Not only were RSME and mental demand rated lower for the water polo video-based test, but so were RPE and physical demand, despite the identical exercise protocol during the two sessions. In contrast, in a study by Vera et al. (2018), male sport science students did not report different RPE for two cognitive tasks of differing mental load that were performed while cycling. The tasks used by Vera et al. (2018) (2-back and oddball) were designed to differ only in their mental demand. The fact that, in the present study, participants rated perceived exertion and physical demand greater in the Stroop condition, and not just mental demand and RSME, suggests that the Stroop and water polo video-based tests did not only differ in the executive demands or "how hard" it was. Indeed, other differences, such as sport specificity, could be contributing factors. Previous research has highlighted how prolonged cognitive effort can affect subsequent physical performance capacity via increased RPE (McMorris et al., 2018; Pageaux & Lepers, 2016; Staiano et al., 2023; Van Cutsem & Marcora, 2021), and the present results provide evidence to suggest interactions may exist for shorter, dual-task contexts. The nature of the cognitive task – whether it was complexity, domain-specificity, cognitive functions involved, or a combination – appeared to influence perception of effort such that performing the same physical task resulted in higher RPE and ratings of physical demand. Indeed, while acknowledging the two tasks in the present study differed in response modality (small motor movement *vs*. verbal response), seeming differences in RT between the Stroop task and the water polo video-based test could potentially reflect different cognitive resources solicited.

Interestingly, for affect, there were no differences between tasks. It is possible the shorter duration of this dual task could explain why affect was not lower during the task perceived as more mentally demanding, as was the case in the study by Vera et al. (2018). Among the females, affect was no different between HICE and HIIE and both were significantly lower compared to MICE, mirroring the results obtained by Dierkes et al. (2021). Previous comparisons between sexes of affect during high-intensity interval exercise has found females to report more positive affect than males (Astorino & Sheard, 2019), or no differences between groups (Marques et al., 2020). However, sex differences in the current study should be interpreted cautiously given the relatively small and unequal sample size. However, it reinforces the interest in further research across different population groups to identify if there are sex-specific factors that could contribute to different affective responses. Notably, affect was significantly positively correlated with Stroop accuracy on executive trials. This is coherent with da Silva et al. (2017)'s finding that above the ventilatory threshold, participants exhibited significant decreases in both affect and Stroop performance. According to the dual-mode theory of affective responses to exercise, affect results from the interactions of cognitive processes mainly originating from the prefrontal cortex and exercise-provoked interoceptive cues (Ekkekakis et al., 2020). A dominant contribution of interoceptive cues at high intensities is proposed to be due to amplification of these cues as metabolic strain increases, but also to hypoactivation of the prefrontal cortex (Ekkekakis et al., 2020), which has been supported by decreases in prefrontal oxygenation at high intensities (Bhambhani et al., 2007; Ekkekakis, 2009; Rooks et al., 2010). As an adaptational response, this would serve to ensure homeostatic disruptions, unfiltered by cognitive interference, are brought to conscious awareness (Ekkekakis, 2009). Thus, decreased ratings of affect associated with higher exercise intensities may reflect more salient interoceptive feedback. Based on the interoception model for the acute exercise-cognition interaction (McMorris, 2021), this would contribute to perception of effort costs which, when superior to perceived resources available or worthwhileness of the task, result in impaired executive function performance. Equivocal support for the transient hypofrontality model of executive function during exercise, based on measures of prefrontal oxygenation (e.g., Jung et al., 2024; Kimura et al., 2022; Liu et al., 2023; Mekari et al., 2015; Schmit et al., 2015; Stevens et al., 2018; Stone et al., 2020; Tempest et al., 2017; Zheng et al., 2022), may in part be due to how interoceptive cues – rendered more salient by hypoactivation of the prefrontal cortex (Ekkekakis et al., 2020) – are evaluated in relation to the task, which in turn determine the characteristics of consequent catecholamine release and the effects on executive task performance (McMorris, 2021). While researchers have included cerebral oxygenation measures with self-reported responses, such as arousal (Zheng et al., 2022) and associative-dissociative attention (Jung et al., 2024), the current results justify the continued application of self-report measures as a means to shed light on mechanistic relationships and interactions underlying behavioural and (neuro)physiological measures in studies examining EF during exercise.

3.7.3 Limitations

While EF is required for the complex decision making players make during gameplay, and performance on standardized EF tasks was predictive of performance on a sport-specific computerized decision-making task among youth soccer players (Heisler et al., 2023), the extent to which sport-specific video-based tests solicit EF is still to be determined. Thus, we made a more cautious analysis choice to not treat the Stroop task and the water polo video-based task as equivalent tests and compare them directly within the same statistical model, but still discuss similarities and differences in the results for the two tasks. Furthermore, although the duration of both tasks were similar, due to the nature of the water polo video-based test, there were fewer responses per exercise condition compared to the Stroop task, and the lower number was not suitable to conduct analyses related to the time of cognitive assessment for this task. Lastly, as is common with data collection within the schedule and injury status constraints of high-calibre athletes, our sample size may have resulted in insufficient power to detect intensity-related effects. This may be particularly applicable for the water polo video-based test, for which there were fewer data points per participant included in the statistical models compared to the Stroop test (in which participants' performance was extracted for each trial type and period, as well as exercise condition).

3.8 Conclusion

This study investigated performance by water polo players on both a domain-general and domain-specific cognitive task during different exercise conditions. Notably, exercise duration was considered, and in addition to exercise intensity, exercise modality was also manipulated. Furthermore, the inclusion of self-reported measures revealed intriguing differences that may help explain patterns of performance. Results demonstrated that the athletes, during HICE and HIIE, did not exhibit purely exercise intensity-related decrements in EF, a phenomenon often observed among non-athlete participants. However, by segmenting task performance in time into early, middle, and late periods, it was found that exercise duration may negatively impact RT speed, both independently and in interaction with exercise intensity. The modality of high-intensity exercise, i.e., continuous or interval, did not influence performance nor on self-reported measures, but there emerged interesting differences between the two tasks. There were no significant exercise-intensity related effects on performance of the video-based task, and quite fascinatingly, it was perceived to be less effortful and of lower demand than the Stroop task – mentally and physically. Additionally, Stroop accuracy was positively correlated with affect and negatively correlated with self-reported physical demand. This highlights the importance of considering self-reported measures and their potential in enriching the understanding of behavioural outcomes in dual-task contexts. Together, these results suggest population- or expertise-specific cognitive performance during exercise and justify further exploration of the temporal dynamics of exercise and cognition as well as of the impact of participant perceptions – for both domain-general and domain-specific tasks.

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Declaration of interest: The authors declare no competing interests.

Data availability statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

3.9 Supplementary material

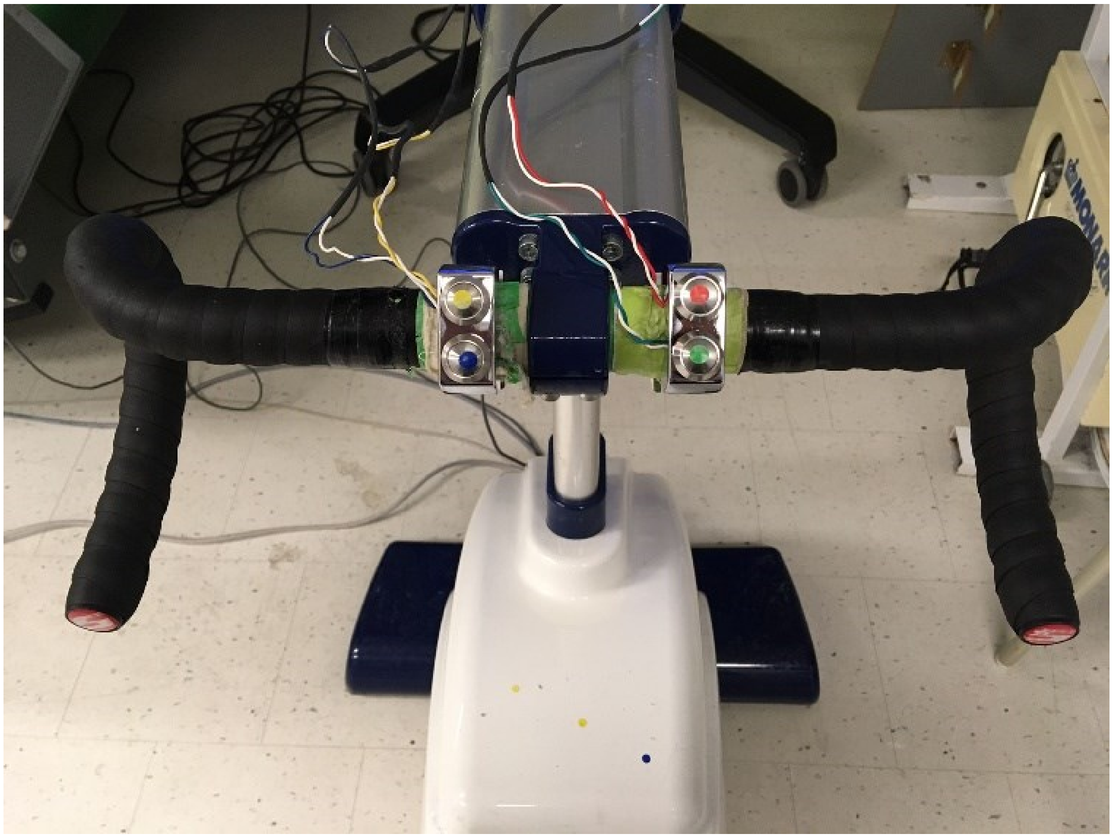

Figure 3.7. Buttons used by participants to respond to the Stroop task.

3.9.1 Section S1: Detailed values for the Stroop RT (non-dynamical perspective) analyses.

Table S1.1. Estimated marginal means of *Cognitive trial type* * *Exercise condition* interaction for the linear mixed model conducted on Stroop RT (non-dynamical perspective).

Cognitive trial type	Exercise condition	emmean	SE	df	lower.CL	upper.CL
inhibition	MICE	847.2056	20.07897	46.81337	806.8077	887.6035
naming	MICE	613.9183	20.07897	46.81337	573.5204	654.3162
switch	MICE	897.4975	20.07897	46.81337	857.0995	937.8954
inhibition	HICE	836.9325	20.07897	46.81337	796.5346	877.3305
naming	HICE	691.8785	20.07897	46.81337	651.4806	732.2764
switch	HICE	914.4112	20.07897	46.81337	874.0133	954.8092
inhibition	HIIE	862.1741	20.07897	46.81337	821.7762	902.5721
naming	HIIE	693.7500	20.07897	46.81337	653.3520	734.1479
switch	HIIE	920.1521	20.07897	46.81337	879.7542	960.5500

Table S1.1.1. Pairwise comparisons by Cognitive trial type of the estimated differences for *Exercise condition* by *Cognitive trial* type for the linear mixed model conducted on Stroop RT (non-dynamical perspective).

contrast	Cognitive trial type	estimate	SE	df	lower.CL	upper.CL
MICE - HICE	inhibition	10.273062	20.78551	132	-40.12917	60.67529
MICE - HIIE	inhibition	-14.968539	20.78551	132	-65.37077	35.43369
HICE - HIIE	inhibition	-25.241601	20.78551	132	-75.64383	25.16063
MICE - HICE	naming	-77.960207	20.78551	132	-128.36244	-27.55798
MICE - HIIE	naming	-79.831656	20.78551	132	-130.23389	-29.42943
HICE - HIIE	naming	-1.871449	20.78551	132	-52.27368	48.53078
MICE - HICE	switch	-16.913761	20.78551	132	-67.31599	33.48847
MICE - HIIE	switch	-22.654626	20.78551	132	-73.05686	27.74760
HICE - HIIE	switch	-5.740866	20.78551	132	-56.14310	44.66136

3.9.2 Section S2: Detailed values for the Stroop RT (dynamical perspective) analyses.

Table S2.1. Estimated marginal means of *Period * Exercise condition* interaction for the linear mixed model conducted on Stroop RT (dynamical perspective).

Exercise condition	Period	emmean	SE	df	lower.CL	upper.CL
MICE	early	803.0071	18.14371	35.91921	766.207	839.8071
HICE	early	789.4134	18.14371	35.91921	752.6133	826.2134
HIIE	early	806.0842	18.14371	35.91921	769.2841	842.8842
MICE	middle	772.345	18.14371	35.91921	735.545	809.145
HICE	middle	845.1244	18.14371	35.91921	808.3243	881.9244
HIIE	middle	815.3829	18.14371	35.91921	778.5829	852.1829
MICE	qlate	777.2438	18.14371	35.91921	740.4438	814.0438
HICE	qlate	811.7712	18.14371	35.91921	774.9711	848.5712
HIIE	qlate	848.1837	18.14371	35.91921	811.3836	884.9837

Table S2.1.1. Pairwise comparisons by Cognitive trial type of the estimated differences for *Period * Exercise condition* interaction for the linear mixed model conducted on Stroop RT (dynamical perspective).

contrast	Cognitive trial type	estimate	SE	df	lower.CL	upper.CL
early - middle	MICE	30.66205	15.74928	440	-7.18613	68.51023
early - qlate	MICE	25.76328	15.74928	440	-12.0849	63.61146
middle - qlate	MICE	-4.89877	15.74928	440	-42.7469	32.94942
early - middle	HICE	-55.711	15.74928	440	-93.5592	-17.8628
early - qlate	HICE	-22.3578	15.74928	440	-60.206	15.49036
middle - qlate	HICE	33.35319	15.74928	440	-4.49499	71.20137
early - middle	HIIE	-9.29876	15.74928	440	-47.1469	28.54942
early - qlate	HIIE	-42.0995	15.74928	440	-79.9477	-4.25131
middle - qlate	HIIE	-32.8007	15.74928	440	-70.6489	5.047451

Table S2.1.2. Pairwise comparisons by Period of the estimated differences for *Period * Exercise condition* interaction for the linear mixed model conducted on Stroop RT (dynamical perspective).

contrast	Period	estimate	SE	df	lower.CL	upper.CL
MICE - HICE	early	13.59371	15.77379	440	-24.3134	51.5008
MICE - HIIE	early	-3.0771	15.77379	440	-40.9842	34.82999
HICE - HIIE	early	-16.6708	15.77379	440	-54.5779	21.23628
MICE - HICE	middle	-72.7793	15.77379	440	-110.686	-34.8723
MICE - HIIE	middle	-43.0379	15.77379	440	-80.945	-5.13081
HICE - HIIE	middle	29.74144	15.77379	440	-8.16565	67.64853
MICE - HICE	qlate	-34.5274	15.77379	440	-72.4345	3.379701
MICE - HIIE	qlate	-70.9399	15.77379	440	-108.847	-33.0328
HICE - HIIE	qlate	-36.4125	15.77379	440	-74.3196	1.494608

Table S2.2. Estimated marginal means of *Period * Cognitive trial type* interaction for the linear mixed model conducted on Stroop RT (dynamical perspective).

Cognitive trial type	Period	emmean	SE	df	lower.CL	upper.CL
inhibition	early	860.0238	18.13661	35.86456	823.2363	896.8114
naming	early	649.8881	18.13661	35.86456	613.1006	686.6757
switch	early	888.5926	18.13661	35.86456	851.805	925.3802
inhibition	middle	840.7793	18.13661	35.86456	803.9918	877.5669
naming	middle	681.1978	18.13661	35.86456	644.4102	717.9854
switch	middle	910.8751	18.13661	35.86456	874.0876	947.6627
inhibition	qlate	842.0474	18.13661	35.86456	805.2598	878.835
naming	qlate	665.1399	18.13661	35.86456	628.3523	701.9275
switch	qlate	930.0113	18.13661	35.86456	893.2237	966.7989

Table S2.2.1. Pairwise comparisons by Cognitive trial type of the estimated differences for *Period * Cognitive trial type* interaction for the linear mixed model conducted on Stroop RT (dynamical perspective).

contrast	Cognitive trial type	estimate	SE	df	lower.CL	upper.CL
early - middle	inhibition	19.24448	15.74928	440	-18.6037	57.09266
early - qlate	inhibition	17.97642	15.74928	440	-19.8718	55.8246
middle - qlate	inhibition	-1.26806	15.74928	440	-39.1162	36.58012
early - middle	naming	-31.3097	15.74928	440	-69.1579	6.538497
early - qlate	naming	-15.2518	15.74928	440	-53.1	22.5964
middle - qlate	naming	16.05791	15.74928	440	-21.7903	53.90609
early - middle	switch	-22.2825	15.74928	440	-60.1307	15.56566
early - qlate	switch	-41.4187	15.74928	440	-79.2669	-3.57049
middle - qlate	switch	-19.1362	15.74928	440	-56.9843	18.71202

Table S2.2.2. Pairwise comparisons by Period of the estimated differences for *Period * Cognitive trial type* interaction for the linear mixed model conducted on Stroop RT (dynamical perspective).

contrast	Cognitive trial type	estimate	SE	df	lower.CL	upper.CL
inhibition - naming	early	210.1357	15.74928	440	172.2875	247.9839
inhibition - switch	early	-28.5688	15.74928	440	-66.417	9.279388
naming - switch	early	-238.704	15.74928	440	-276.553	-200.856
inhibition - naming	middle	159.5815	15.74928	440	121.7333	197.4297
inhibition - switch	middle	-70.0958	15.74928	440	-107.944	-32.2476
naming - switch	middle	-229.677	15.74928	440	-267.525	-191.829
inhibition - naming	qlate	176.9075	15.74928	440	139.0593	214.7557
inhibition - switch	qlate	-87.9639	15.74928	440	-125.812	-50.1157
naming - switch	qlate	-264.871	15.74928	440	-302.72	-227.023

Table S2.3. Estimated marginal means of *Exercise condition* * *Cognitive trial type* interaction for the linear mixed model conducted on Stroop RT (dynamical perspective).

Cognitive trial type	Exercise condition	emmean	SE	df	lower.CL	upper.CL
inhibition	MICE	844.9531	18.14371	35.91921	808.153	881.7531
naming	MICE	612.3227	18.14371	35.91921	575.5227	649.1227
switch	MICE	895.3201	18.14371	35.91921	858.5201	932.1202
inhibition	HICE	836.7768	18.14371	35.91921	799.9768	873.5769
naming	HICE	692.0969	18.14371	35.91921	655.2969	728.8969
switch	HICE	917.4352	18.14371	35.91921	880.6351	954.2352
inhibition	HIIE	861.1207	18.14371	35.91921	824.3206	897.9207
naming	HIIE	691.8063	18.14371	35.91921	655.0063	728.6063
switch	HIIE	916.7238	18.14371	35.91921	879.9237	953.5238

Table S2.3.1. Pairwise comparisons by Cognitive trial type of the estimated differences for *Exercise condition* * *Cognitive trial type* interaction for the linear mixed model conducted on Stroop RT (dynamical perspective).

contrast	Cognitive trial type	estimate	SE	df	lower.CL	upper.CL
MICE - HICE	inhibition	8.176231	15.77379	440	-29.7309	46.08332
MICE - HIIE	inhibition	-16.1676	15.77379	440	-54.0747	21.73949
HICE - HIIE	inhibition	-24.3438	15.77379	440	-62.2509	13.56325
MICE - HICE	naming	-79.7742	15.77379	440	-117.681	-41.8671
MICE - HIIE	naming	-79.4836	15.77379	440	-117.391	-41.5765
HICE - HIIE	naming	0.290586	15.77379	440	-37.6165	38.19767
MICE - HICE	switch	-22.115	15.77379	440	-60.0221	15.79205
MICE - HIIE	switch	-21.4036	15.77379	440	-59.3107	16.50345
HICE - HIIE	switch	0.711398	15.77379	440	-37.1957	38.61849

Table S2.3.2. Pairwise comparisons by Exercise condition of the estimated differences for *Exercise condition* * *Cognitive trial type* interaction for the linear mixed model conducted on Stroop RT (dynamical perspective).

contrast	Exercise condition	estimate	SE	df	lower.CL	upper.CL
inhibition - naming	MICE	232.6304	15.74928	440	194.7822	270.4786
inhibition - switch	MICE	-50.3671	15.74928	440	-88.2152	-12.5189
naming - switch	MICE	-282.997	15.74928	440	-320.846	-245.149
inhibition - naming	HICE	144.6799	15.74928	440	106.8318	182.5281
inhibition - switch	HICE	-80.6583	15.74928	440	-118.507	-42.8101
naming - switch	HICE	-225.338	15.74928	440	-263.186	-187.49
inhibition - naming	HIIE	169.3144	15.74928	440	131.4662	207.1625
inhibition - switch	HIIE	-55.6031	15.74928	440	-93.4513	-17.7549
naming - switch	HIIE	-224.917	15.74928	440	-262.766	-187.069

Table S2.4. Estimated marginal means of *Sex* main effect for the linear mixed model conducted on Stroop RT (dynamical perspective).

Sex	emmean	SE	df	lower.CL	upper.CL
f	738.299	24.14936	16	687.1046	789.4933
m	876.9356	17.07617	16	840.7357	913.1355

Table S2.4.1. Pairwise comparisons of the estimated difference for *Sex* main effect for the linear mixed model conducted on Stroop RT (dynamical perspective).

contrast	estimate	SE	df	lower.CL	upper.CL
f - m	-138.637	29.5768	16	-201.337	-75.9366

Table S2.5. Estimated marginal means of *Exercise order* main effect for the linear mixed model conducted on Stroop RT (dynamical perspective).

Exercise order	emmean	SE	df	lower.CL	upper.CL
1	824.4759	15.70077	20.31721	791.7574	857.1944
2	799.2082	15.70077	20.31721	766.4897	831.9267
3	799.1678	15.70077	20.31721	766.4493	831.8863

Table S2.5.1. Pairwise comparisons of the estimated differencess for *Exercise order* main effect for the linear mixed model conducted on Stroop RT (dynamical perspective).

contrast	estimate	SE	df	lower.CL	upper.CL
1-2	25.26772	9.135242	440	3.314187	47.22125
1-3	25.30808	9.135242	440	3.354547	47.26161
2-3	0.04036	9.135242	440	-21.9132	21.99389

3.9.3 Section S3: Detailed values for RPE analyses.

Table S3.1. Estimated marginal means of *Exercise condition* main effect for the linear mixed model conducted on RPE.

Exercise condition	emmean	SE	df	lower.CL	upper.CL
MICE	5.671498	0.289643	36.07998	5.08412	6.258876
HICE	7.522688	0.289643	36.07998	6.935311	8.110066
HIIE	7.70126	0.289643	36.07998	7.113882	8.288638

Table S3.1.1. Pairwise comparisons of the estimated differencess for *Exercise condition* main effect for the linear mixed model conducted on RPE.

contrast	estimate	SE	df	lower.CL	upper.CL
MICE - HICE	-1.85119	0.297564	77.0695	-2.57944	-1.12295
MICE - HIIE	-2.02976	0.297564	77.0695	-2.75801	-1.30152
HICE - HIIE	-0.17857	0.297564	77.0695	-0.90682	0.549674

Table S3.2. Estimated marginal means of *Task* main effect for the linear mixed model conducted on RPE.

Task	emmean	SE	df	lower.CL	upper.CL
Stroop	7.249472	0.254823	23.07305	6.722423	7.776521
Water polo video-based	6.680826	0.265841	25.82406	6.134201	7.22745

Table S3.2.1. Pairwise comparisons of the estimated difference for *Task* main effect for the linear mixed model conducted on RPE.

contrast	estimate	SE	df	lower.CL	upper.CL
Stroop – Water polo video-based	0.568646	0.23173	79.91058	0.10748	1.029812

3.9.4 Section S4: Detailed values for affect analyses.

Table S4.1. Estimated marginal means of *Exercise condition* * *Sex* interaction for the linear mixed model conducted affect.

Exercise condition	Sex	emmean	SE	df	lower.CL	upper.CL
MICE	f	1.596468	0.909588	21.39768	-0.29299	3.485922
HICE	f	-0.32207	0.909588	21.39768	-2.21152	1.567388
HIIE	f	-0.78005	0.909588	21.39768	-2.6695	1.109405
MICE	m	1.177477	0.639547	20.95256	-0.15272	2.50767
HICE	m	0.564265	0.639547	20.95256	-0.76593	1.894458
HIIE	m	0.736534	0.639547	20.95256	-0.59366	2.066727

Table S4.1.1. Pairwise comparisons by Sex for the estimated differencess of *Exercise condition* * *Sex* interaction for the linear mixed model conducted on affect.

contrast	Sex	estimate	SE	df	lower.CL	upper.CL
MICE - HICE	f	1.918534	0.577744	77.00701	0.504563	3.332505
MICE - HIIE	f	2.376517	0.577744	77.00701	0.962546	3.790489
HICE - HIIE	f	0.457983	0.577744	77.00701	-0.95599	1.871955
MICE - HICE	m	0.613212	0.399268	77.00701	-0.36396	1.590381
MICE - HIIE	m	0.440943	0.399268	77.00701	-0.53623	1.418112
HICE - HIIE	m	-0.17227	0.399268	77.00701	-1.14944	0.8049

Table S4.1.2. Pairwise comparisons by Exercise condition for the estimated differencess of *Exercise condition* * *Sex* interaction for the linear mixed model conducted on affect.

contrast	Exercise condition	estimate	SE	df	lower.CL	upper.CL
f - m	MICE	0.418991	1.111577	21.22642	-1.89116	2.729142
f - m	HICE	-0.88633	1.111577	21.22642	-3.19648	1.42382
f - m	HIIE	-1.51658	1.111577	21.22642	-3.82673	0.793568

3.9.5 Section S5: Detailed values for mental demand analyses.

Table S5.1. Estimated marginal means of *Exercise condition* main effect for the linear mixed model conducted on mental demand.

Exercise condition	emmean	SE	df	lower.CL	upper.CL
MICE	60.38042	4.549366	22.67302	50.96183	69.79902
HICE	66.1176	4.633131	23.97952	56.55486	75.68035
HIIE	70.05079	4.548501	22.66258	60.63374	79.46784

Table S5.1.1. Pairwise comparisons of the estimated differencess for *Exercise condition* main effect for the linear mixed model conducted on mental demand.

contrast	estimate	SE	df	lower.CL	upper.CL
MICE - HICE	-5.73718	3.268855	74.52256	-13.7433	2.268963
MICE - HIIE	-9.67037	3.190317	74.02613	-17.4854	-1.85537
HICE - HIIE	-3.93319	3.273916	74.55327	-11.9517	4.085279

Table S5.2. Estimated marginal means of *Exercise order* main effect for the linear mixed model conducted on mental demand.

Exercise order	emmean	SE	df	lower.CL	upper.CL
1	61.1809	4.505106	21.82834	51.83362	70.52818
2	66.27039	4.505164	21.82912	56.92301	75.61777
3	69.09753	4.562775	22.7028	59.65186	78.54319

Table S5.2.1. Pairwise comparisons of the estimated differences for *Exercise order* main effect for the linear mixed model conducted on mental demand.

Exercise order	estimate	SE	df	lower.CL	upper.CL
1-2	-5.08949	2.984192	74.02559	-12.3996	2.220581
1-3	-7.91663	3.02965	74.33728	-15.3373	-0.49592
2-3	-2.82713	3.029461	74.33602	-10.2474	4.593114

Table S5.3. Estimated marginal means of *Task* main effect for the linear mixed model conducted on mental demand.

Task	emmean	SE	df	lower.CL	upper.CL
Stroop	70.33941	4.31767	18.54349	61.28734	79.39148
Water polo video-based	60.69313	4.398512	19.69459	51.50887	69.8774

Table S5.3.1. Pairwise comparisons of the estimated difference for *Task* main effect for the linear mixed model conducted on mental demand.

contrast	estimate	SE	df	lower.CL	upper.CL
Stroop – Water polo video-based	9.646276	2.492558	75.20378	4.681066	14.61149

3.9.6 Section S6: Detailed values for physical demand analyses.

Table S6.1. Estimated marginal means of *Exercise condition* main effect for the linear mixed model conducted on physical demand.

Exercise condition	emmean	SE	df	lower.CL	upper.CL
MICE	64.44294	3.005647	31.47651	58.31664	70.56924
HICE	76.49261	3.005647	31.47651	70.36631	82.61891
HIIE	80.0312	3.005647	31.47651	73.9049	86.1575

Table S6.1.1. Pairwise comparisons of the estimated differencess for *Exercise condition* main effect for the linear mixed model conducted on physical demand.

contrast	estimate	SE	df	lower.CL	upper.CL
MICE - HICE	-12.0497	2.843628	75.04528	-19.0132	-5.08611
MICE - HIIE	-15.5883	2.843628	75.04528	-22.5518	-8.62471
HICE - HIIE	-3.53859	2.843628	75.04528	-10.5021	3.424958

Table S6.2. Estimated marginal means of *Task* main effect for the linear mixed model conducted on physical demand.

Task	emmean	SE	df	lower.CL	upper.CL
Stroop	76.01161	2.700377	21.39516	70.40217	81.62104
Water polo video-based	71.29956	2.798938	23.76371	65.5198	77.07933

Table S6.2.1. Pairwise comparisons of the estimated difference for *Task* main effect for the linear mixed model conducted on physical demand.

contrast	estimate	SE	df	lower.CL	upper.CL
Stroop – Water polo video-based	4.712044	2.213174	77.39288	0.305409	9.11868

3.9.7 Section S7: Detailed values for RSME analyses.

Table S7.1. Estimated marginal means of *Exercise condition* main effect for the linear mixed model conducted on RSME.

Exercise condition	emmean	SE	df	lower.CL	upper.CL
MICE	77.65431	4.261339	24.47599	68.86838	86.44024
HICE	92.02336	4.261339	24.47599	83.23743	100.8093
HIIE	93.78446	4.261339	24.47599	84.99853	102.5704

Table S7.1.1. Pairwise comparisons of the estimated differences for *Exercise condition* main effect for the linear mixed model conducted on RSME.

contrast	estimate	SE	df	lower.CL	upper.CL
MICE - HICE	-14.369	3.254243	75.01626	-22.3382	-6.3999
MICE - HIIE	-16.1301	3.254243	75.01626	-24.0993	-8.161
HICE - HIIE	-1.7611	3.254243	75.01626	-9.73024	6.208052

Table S7.2. Estimated marginal means of *Exercise order* main effect for the linear mixed model conducted on RSME.

Exercise order	emmean	SE	df	lower.CL	upper.CL
1	82.42059	4.209247	23.36907	73.7207	91.12048
2	89.12374	4.209247	23.36907	80.42386	97.82363
3	91.9178	4.209247	23.36907	83.21791	100.6177

Table S7.2.1. Pairwise comparisons of the estimated differences for *Exercise order* main effect for the linear mixed model conducted on RSME.

Exercise order	estimate	SE	df	lower.CL	upper.CL
1-2	-6.70316	3.044065	75.01626	-14.1576	0.751299
1-3	-9.49721	3.044065	75.01626	-16.9517	-2.04275
2-3	-2.79405	3.044065	75.01626	-10.2485	4.660401

Table S7.3. Estimated marginal means of *Task* main effect for the linear mixed model conducted on RSME.

Task	emmean	SE	df	lower.CL	upper.CL
Stroop	93.68377	3.983189	18.95534	85.34553	102.022
Water polo video-based	81.95765	4.076663	20.49682	73.46708	90.44823

Table S7.3.1. Pairwise comparisons of the estimated difference for *Task* main effect for the linear mixed model conducted on RSME.

contrast	estimate	SE	df	lower.CL	upper.CL
Stroop – Water polo video-based	11.72611	2.540477	76.53672	6.666888	16.78534

This study investigated cognitive performance during different exercise conditions, which is relevant considering that athletes are often faced with simultaneous mental and physical demands. However, physical load is not synonymous with fatigue, and if we were to understand the effects of fatigue on performance, a more targeted exploration was necessary.

CHAPTER 4

THE EFFECTS OF FATIGUE ON PERCEPTUAL-COGNITIVE PERFORMANCE AMONG OPEN-SKILL SPORT ATHLETES: A SCOPING REVIEW

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4.1 Abstract

Perceptual-cognitive performance is fundamental for the anticipation and decision-making demands of open-skill sports but may be disrupted by fatigue. This scoping review aimed to describe what is known about the effects of fatigue on perceptual-cognitive performance among open-skill sport athletes. Six databases were systematically searched. Articles were included if they involved open-skill sport athletes, a perceptual-cognitive task assessed on two or more occasions, and induction of acute fatigue confirmed by a manipulation check. Sixty-seven studies, chapters, and reviews were included. In 51% of studies, fatigue was induced through physical exertion, with the rest by mental exertion (27%), or a combination of physical and mental exertion (22%). Only 35% of studies involved sport-specific exertion to induce fatigue, and 29% included measures of participants' subjective ratings that confirmed the presence of fatigue. Forty-seven percent of perceptual-cognitive tasks were sport-specific and just 19% assessed perceptual-cognitive performance simultaneous to the fatigue-inducing exertion. Negative, positive, and no effects of fatigue on perceptual-cognitive performance were reported and these equivocal findings may be attributable to methodological discrepancies between studies. Future research should include more sport-specific designs, as well as stressors other than fatigue, such as environmental and psychosocial stressors.

Keywords: strategic; interceptive; decision making, anticipation; perceptual-cognitive skills

4.2 Introduction

High-level athletes require impressive physical and technical abilities, but they must also demonstrate outstanding perceptual-cognitive skills (Williams et al., 1999). Open-skill sport athletes, in particular, may face greater perceptual-cognitive demands (Koch & Krenn, 2021; Krenn et al., 2018). Despite equivocal terminologies and definitions (Table 4.1), open-skill (i.e., interceptive and strategic) sports are distinguishable from closed-skill (i.e., static) sports in how they occur within a dynamic context and require fast anticipation and decision making. Open-skill sport athletes rely on perceptual-cognitive skills: the ability to extract relevant environmental information and integrate it with existing knowledge to execute an appropriate response (Marteniuk, 1976). Accordingly, any deviation from optimal perceptual-cognitive performance could have important consequences for game outcomes. One potentially disrupting factor is fatigue. Indeed, interviews with coaches support the notion of decision making becoming more difficult as fatigue develops during gameplay (Morgan et al., 2020). However, existing reviews are insufficient to understand this phenomenon, and inconsistent and incomplete conceptualizations of fatigue, as well as the multitude of different perceptual-cognitive tasks used in studies (Enoka & Duchateau, 2016; Pageaux & Lepers, 2016, 2018), pose challenges in scrutinizing if and how fatigue affects perceptual-cognitive performance.

Acute (i.e., performed within a day (Chang et al., 2012)) exercise effects on cognition have been the subject of previous research. Theoretical explanations, including exercise-induced increases in catecholamine release and in hypothalamus-pituitary-adrenal axis hormones, and changes in cerebral oxygenation, have been used to predict that moderate exercise would facilitate, while heavy exercise would impair, cognitive performance (Dietrich & Audiffren, 2011; McMorris et al., 2015). However, in addition to exercise intensity, participant fitness (Brisswalter et al., 2002; Browne et al., 2017), type of exercise (Lambourne & Tomporowski, 2010; Schapschroer, Lemez, et al., 2016), as well as cognitive task type (Browne et al., 2017; Chang et al., 2012; Lambourne & Tomporowski, 2010; McMorris & Hale, 2012; McMorris et al., 2016; Schapschroer, Lemez, et al., 2016) and timing of assessment (Lambourne & Tomporowski, 2010) could play roles in the acute exercise and cognition relationship. Another element that may help to explain equivocal results is the duration of the exercise (Schmit & Brisswalter, 2020). Intuitively, jogging and sprinting performed for the same duration are not equivalent. Under this dynamical view, it is proximity to exhaustion – a factor of intensity *and* duration – that determines whether complex cognitive functioning is enhanced or impaired. As the participant nears exhaustion, the metabolic, neurochemical, and hormonal disruptions; shifts in attentional allocation; and competition between exercise- and task-related demands for frontal brain resources may result in impaired perceptual-cognitive performance (Fox et al., 2005; McMorris et al., 2016). Examining fatigue effects specifically (as opposed to just exercise effects) is thus supported methodologically by this dynamical perspective and practically by its relevance to the context of open-skill sports, where athletes aim to sustain maximal performance for prolonged periods.

Table 4.1. Sport classifications existing in the literature.

Key references	**Category**	**Defining features**	**Examples**
Allard and Burnett (1985); Singer (2000)	Closed-skill or internally-paced	Involve predetermined movement patterns and occur in stable environments with predictable situations	Gymnastics, sprinting, golf, swimming
	Open-skill or externally-paced	Involve a constantly changing environment to which participants must dynamically react and adapt, reading their opponents and other cues to quickly respond while under time constraints	Badminton, soccer
Mann et al. (2007); Voss et al. (2010)	Static or "other"	Take place in relatively consistent and self-paced situations	Gymnastics, sprinting, golf, swimming
	Interceptive	Involve coordination between an object in the environment and the athlete's body, parts of the body, or a held implement (Davids et al., 2002)	Badminton, squash, boxing
	Strategic	Involve unpredictable situations in which participants must allocate attention to multiple teammates, opponents, and the projectile (e.g., ball)	Soccer, volleyball, water polo

“Fatigue” remains a complex construct, with a lack of consensus surrounding its definition. Researchers have often distilled the concept of fatigue into “physical” or “muscle” fatigue (e.g., Gandevia, 2001) and “mental” or “cognitive” fatigue (e.g., Marcora et al., 2009). This dichotomization has resulted in studies examining the effects of physical fatigue (e.g., Casanova et al., 2013; Parkin et al., 2017; Royal et al., 2006) or mental fatigue separately (e.g., Gantois et al., 2020; Kosack et al., 2020; Kunrath, Nakamura, et al., 2020; Parkin & Walsh, 2017b; M. R. Smith et al., 2016), but rarely their combined impact (e.g., Alder et al., 2021) on perceptual-cognitive performance (Habay et al., 2021; Soylu et al., 2022; Sun et al., 2021). However, it can be hard to disentangle the physical from the mental, such as when there are simultaneous significant physical and cognitive loads – like during open-skill sport performance (Russell, Kelly, et al., 2020). Thus, although fatigue can result from physical (e.g., volitional test to exhaustion) or mental exertion (e.g., Stroop test), in many real-life situations, physical and mental exertion occur in combination and interact. In these circumstances, designating fatigue as “physical” or “mental” may not capture the full picture. Without sacrificing an indication of how the fatigue is induced, a more holistic and practical approach would be to consider fatigue as a loss in motor and/or cognitive efficiency, alterations of self-regulatory functions (Schmit & Brisswalter, 2020), and/or increased feelings of tiredness that can result from prolonged physical, mental, or a combination of physical and mental exertion (e.g., Pageaux and Lepers (2016)). Such a perspective would reduce the limitations of forcing a label of either physical or mental fatigue when there may be more than one source (Figure 4.1).

Consistent with this operationalization of fatigue, a change in a subjective or objective measure to confirm the loss in motor and/or cognitive efficiency, and/or the increase of feelings of tiredness is essential; otherwise, we risk simply examining the effects of exertion and not fatigue. In other words, unless there is a manipulation check attesting to changes in objective or subjective markers of fatigue, we cannot conclude that fatigue was induced by prolonged engagement in physical, mental or combined physical and mental exertion. Consider going for a jog: once a steady state is reached after the onset of exercise, if heart rate and perception of effort did not increase while maintaining the same pace, and if maximal strength was the same after compared to before, then although the jog was exertion, there was no fatigue induced. This example also illustrates that there can be a large range of methods to validate the presence of fatigue, and which is reflected in the existing literature. Manipulation checks range from self-reported increases in feelings of tiredness or increased perceived effort to maintain performance (Enoka & Stuart, 1992; Gandevia, 2001; Marcora, 2019; Pageaux & Lepers, 2016, 2018), to deficits in an objective performance measure. Finally, in addition to the definition of fatigue and how its development is confirmed, another parameter that varies across studies in sport sciences is the nature of the task inducing fatigue: whether it is sport-specific (e.g., match play) or non-specific (e.g., incremental cycling test) (Figure 4.1). Just as in the sports cognition domain where the expert performance approach emphasizes the specificity of athletes' expertise (Mann et al., 2007), it is plausible that athletes may have adaptations to maintain performance under *sport-specific* fatigue-inducing loads.

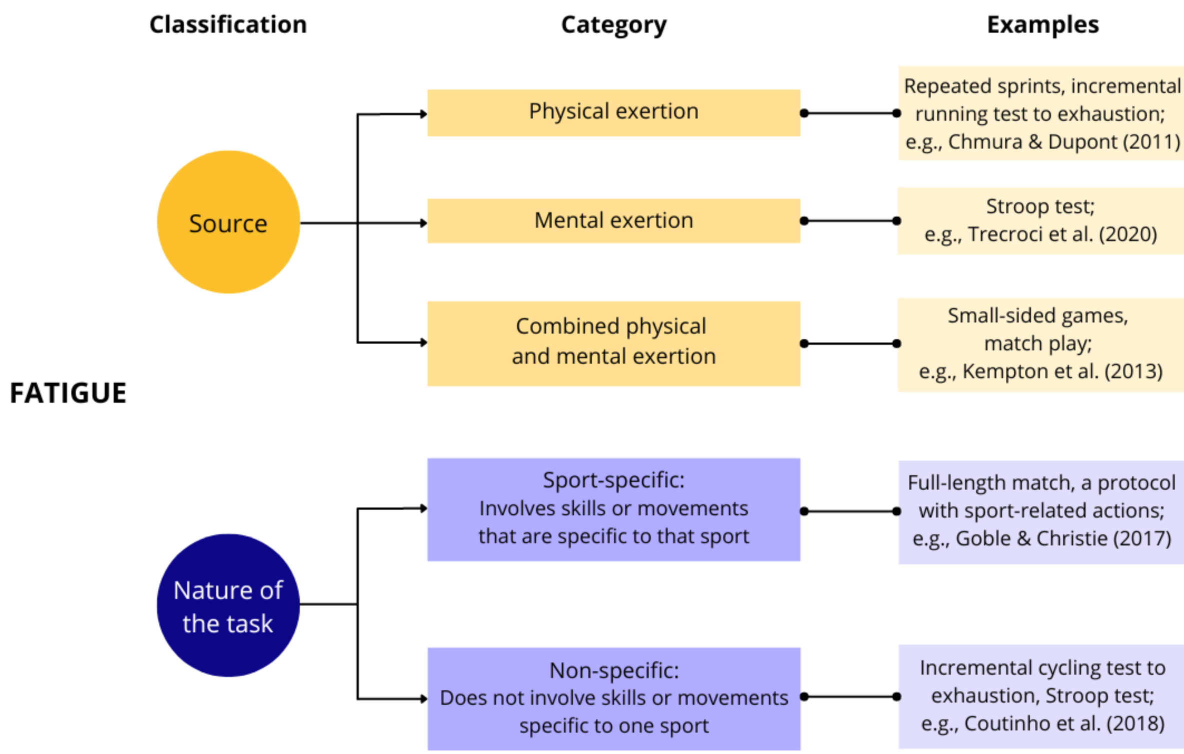

Figure 4.1. Classifications used to describe the fatigue induced.

The complexity of understanding how fatigue affects perceptual-cognitive performance is further exacerbated by the variety of perceptual-cognitive tasks examined in studies and the differences in their task parameters. Like for fatigue, the nature of the perceptual-cognitive task, i.e., if it is sport-specific, such as a video-based decision-making task; or non-specific, such as a traditional choice reaction time test, could be relevant. There is a debate between the aforementioned expert performance perspective

(Mann et al., 2007) and the cognitive components approach, which suggests that expert athletes also demonstrate superior performance on general tests of cognitive functions compared to less-skilled counterparts (Jacobson & Matthaeus, 2014; Logan et al., 2022; Voss et al., 2010). It is however unclear if the effects of fatigue on perceptual-cognitive performance are influenced by the nature of the perceptual-cognitive task (Figure 4.2). Research in sport expertise has additionally suggested the requisite response is a parameter that may moderate performance in the context of sport-specific decision-making tests (Travassos et al., 2013), but it is similarly unclear if the requisite response could play a role in how performance on a perceptual-cognitive task is influenced by fatigue. Finally, evidence that there are sport type-specific cognitive adaptations (Ballester et al., 2019; Jacobson & Matthaeus, 2014; Logan et al., 2022) reinforce the relevance of focusing on open-skill sport athletes.

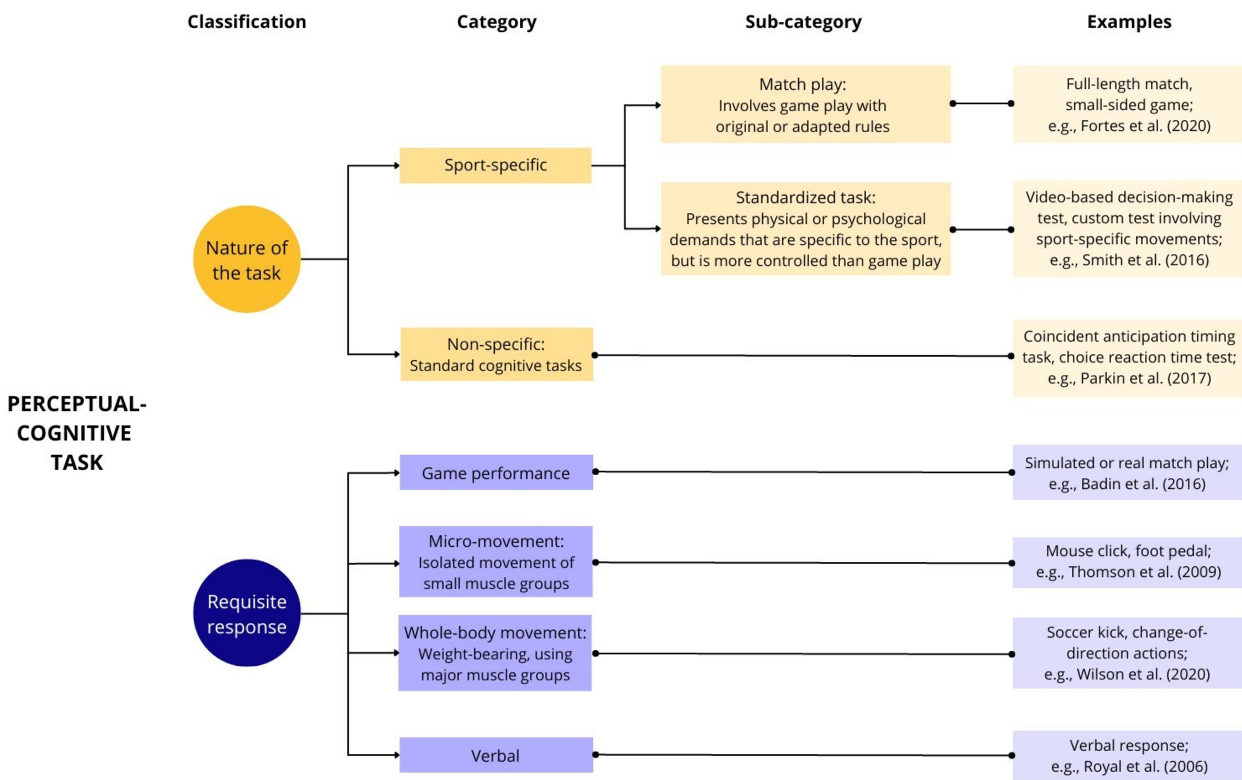

Figure 4.2. Classifications used to describe the perceptual-cognitive task.

Existing reviews point to negative effects of fatigue on sport-related performance, but these often dichotomize fatigue (Pageaux & Lepers, 2016), consider only cognitive fatigue (Aitken & MacMahon, 2019; Habay et al., 2021; McMorris et al., 2018; Pageaux & Lepers, 2018; Sun et al., 2021; Van Cutsem et al., 2017), are centred around effort-based decision making relevant to endurance performance (McMorris et al., 2018; Pageaux & Lepers, 2016; Van Cutsem et al., 2017), also include studies with tasks using pre-planned movements (i.e., that did not require a reaction to the environment, and therefore were not true perceptual-cognitive tasks according to the operationalization above) (Aitken & MacMahon, 2019; Habay et al., 2021; Skala & Zemková, 2022; Sun et al., 2021), and/or do not specifically consider athletes (McMorris et al., 2018; Pageaux & Lepers, 2018; Van Cutsem et al., 2017). Indeed, it has been suggested that athletes, and other populations that are accustomed to performing under strenuous physical loads, require comparatively less activation of motor cortices under high metabolic workloads, allowing for greater resource allocation to the cognitive tasks (Brisswalter et al., 2002; Browne et al., 2017). They may therefore not demonstrate the same fatigue-related performance changes as healthy non-athletes.

In summary, there is a great deal of heterogeneity around the conceptualization of fatigue, the source of the fatigue, the nature of how it is induced, and how its presence is validated. There also exists a variety of perceptual-cognitive task parameters. No other review has addressed fatigue as a holistic construct or examined its effects among open-skill sport athletes – for whom perceptual-cognitive performance is integral to their game – thus warranting a systematic and broad consolidation of the existing literature. The objectives of this scoping review were to synthesize i) the methods used to induce and attest to the presence of fatigue, ii) the methods used to assess perceptual-cognitive performance. We also aimed iii) to describe what is known about the effects of fatigue on perceptual-cognitive performance among open-skill sports athletes.

4.3 Methods

This review was designed and conducted according to the guidelines published by the Johanna Briggs Institute (Peters et al., 2020). A preliminary search of PROSPERO, MEDLINE, the Cochrane Database of Systematic Reviews and the *JBI Evidence Synthesis* yielded no completed or ongoing scoping or systematic reviews on the topic. The protocol was pre-registered with the Open Science Framework (https://osf.io/2bvwj). Consistent with the iterative nature of scoping reviews (Dowling et al., 2020; Levac et al., 2010; Sabiston et al., 2022), there were adjustments made following the preregistration of the protocol: an inclusion list and a data extraction tool were developed specifically for secondary sources of evidence, and the classifications of fatigue and perceptual-cognitive task were refined.

4.3.1 Inclusion criteria

4.3.1.1 Sources of evidence

Both primary literature (original research, including theses and published articles) and secondary literature (reviews, chapters, conference proceedings, editorials, and opinion articles) were included. Primary literature sources needed to include a) healthy, non-injured open-skill sport athletes, or participants who were explicitly reported to have any previous open-skill sport experience; b) induction of acute fatigue confirmed by a manipulation check; and c) a perceptual-cognitive task, for which performance was assessed on two or more occasions (i.e., before and/or during and/or immediately after the fatiguing task). Secondary literature sources needed to a) present or discuss the effects of fatigue/exhaustion on a perceptual-cognitive task; b) contextualize these effects within sport or discussed the relevance to sport performance; and c) have at least one of their populations of interest be open-skill sport athletes.

Sources of evidence were excluded if the full text was not available in English or French, or there was a manipulation of a different independent variable (e.g., nutritional supplementation, heat) but no control group or condition. See Supplementary online material for a detailed list of inclusion criteria.

4.3.1.2 Population

Open-skill sport athletes were considered as those who participated in sports that could be categorized as open skill, externally paced, interceptive, or strategic (Table 4.1).

4.3.1.3 Fatigue

Only texts in which fatigue was induced through mental exertion, physical exertion, or a combination of both physical and mental exertion during the same session as the perceptual-cognitive task were included. Studies also had to include a manipulation check to attest to the presence of fatigue. These were any tests that confirmed, under consistent conditions, decreases in behavioural performance (e.g., slower reaction time, decreased force production capacity) or physiological efficiency (e.g., increase in heart rate without an increase in workload). As fatigue manifests subjectively, too, manipulation checks could also be increases in participants' feelings of tiredness or in the perception of effort to maintain performance in the fatiguing task. Studies that did not report evidence of fatigue but that used a validated fatigue protocol were included (e.g., incremental tests to volitional exhaustion, repeated sprint protocols). Similarly, studies in which participants completed a full-length sports match were included even if there was no manipulation check.

4.3.1.4 Perceptual-cognitive task

Perceptual-cognitive tasks were operationalized as those involving anticipatory decisions (spatial or temporal anticipation), decision making (including choice reaction tests), or traditional tests of executive functions (tests of inhibition, cognitive flexibility, or working memory (Diamond, 2013)). Based on the definition of perceptual-cognitive ability presented earlier, only tasks in which participants were required to select or execute an *appropriate* response *in reaction to* their environment (e.g., stimulus, teammates) were included. Accordingly, tasks in which the action was pre-planned and there was no temporal and/or spatial uncertainty were excluded (e.g., simple reaction time tests, self-paced basketball free throws, Loughborough Soccer Passing Test). Furthermore, only studies in which task performance was assessed for appropriateness using either objective (e.g., response accuracy or ball passing success rate) or subjective (e.g., expert ratings of decision-quality using a standardized scale) methods of evaluation were included. Thus, if outcome measures were quantified but were not either a) considered as a ratio of successful actions to total number of actions or, b) judged for the appropriateness of the response or action, the text was not included.

4.3.2 Search strategy

After consulting with an experienced librarian, six electronic databases were searched from date of inception to April 23, 2021: MEDLINE (EBSCO), SPORTDiscus (EBSCO), PsychINFO, EMBASE, Web of Science, and ProQuest Dissertations and Theses. For the concept of fatigue, some included terms were "muscle fatigue", "mental fatigue", "ego depletion", and "exhaustion". Final search strategies with the detailed list of search terms for each database are available in Supplementary online material. Additional relevant sources of evidence were identified through forward citation searching conducted between August 25-31, 2021.

4.3.3 Screening and selection of sources of evidence

Database search results were imported into CADIMA, an open-access evidence synthesis tool (Kohl et al., 2018). After duplicate removal, all reviewers screened a random sample of 25 titles and abstracts. Discrepancies were discussed, the appropriate modifications were made to the eligibility criteria and definitions document (see Supplementary online material), and 25 new titles and abstracts were screened to confirm consistency. All titles and abstracts were individually filtered by two reviewers and disagreements were resolved by consensus and if needed, by discussion with other reviewers. Full texts were retrieved and similarly filtered by two independent reviewers, with discrepancies resolved by consensus.

4.3.4 Data extraction

All reviewers participated in piloting a data extraction table on three included texts. For experimental studies, the source of the fatigue induced (physical exertion, mental exertion, or a combination of physical and mental exertion) and the nature of the task inducing fatigue (sport-specific or non-specific) were identified (Figure 4.1). The nature of the perceptual-cognitive task and the requisite response were also categorized (Figure 4.2). The results were considered "uninterpretable" if there were other independent variables (e.g., fasting state, sleep deprivation, etc.) included in the analyses such that the exclusive effect of fatigue on the perceptual-cognitive task could not be determined. Data were extracted separately for reviews, chapters, and other articles and included information about the population of interest, the type of fatigue, and the relevant main conclusions. Data extraction was conducted by one reviewer, with consultation with a second reviewer to resolve uncertainties.

4.4 Results

4.4.1 Search and selection of studies

The results of the search, including reasons for exclusion are presented in Figure 4.3 (see Supplementary online material for a detailed flowchart). The initial database search yielded 5722 references, with 54 full texts satisfying inclusion criteria. Ten additional articles were identified through forward citation searching. In total, 64 texts were included: 47 primary literature sources (46 original articles, 1 thesis) and 17 secondary sources of evidence (12 reviews, three chapters, one peer-reviewed opinion article, one conference proceeding). The 64 sources of evidence were categorized and analyzed as 46 experimental studies and 18 reviews, chapters, and other published articles (which included one qualitative original article).

There has been remarkable growth in the number of both primary and secondary literature on the subject (Figure 4.4a). The greatest number of texts came from research groups in Australia (n = 14), the United Kingdom (n = 12), and Brazil (n = 7, Figure 4.4b).

4.4.2 Experimental studies

4.4.2.1 Participants

Forty-six texts with 47 participant groups were considered. There were two separate groups included from Finkenzeller et al. (2019), which featured different studies within the same article. The mean reported age of participants ranged between 13.7 years old (D. Coutinho et al., 2018) and 30.3 years old (H. K. Faro et al., 2020). Studies most frequently (n = 23) involved athletes between 20.0-24.9 years. Four did not report participant age at all (Bradley et al., 2014; Carling & Dupont, 2011; Michailidis et al., 2018; Obmiński et al., 2017). Most studies (53%) exclusively involved male participants, and only two included sex-based analyses (Bradley et al., 2014; Finkenzeller et al., 2019). Twelve studies did not state the sex, but for 11 of these, other contextual information (e.g., the league in which participants played, anthropometric measures) made it reasonable to suspect participants were male: this group of participants is described as “presumably male”. Overall, there were far more male participants (up to

82.8%), with females accounting for only 16.3% of participants (Figure 4.5a). Furthermore, 4% of study designs exclusively included females, and 15% included both female and male participants.

Figure 4.3. PRISMA flow chart for the identification, screening, and inclusion of articles.

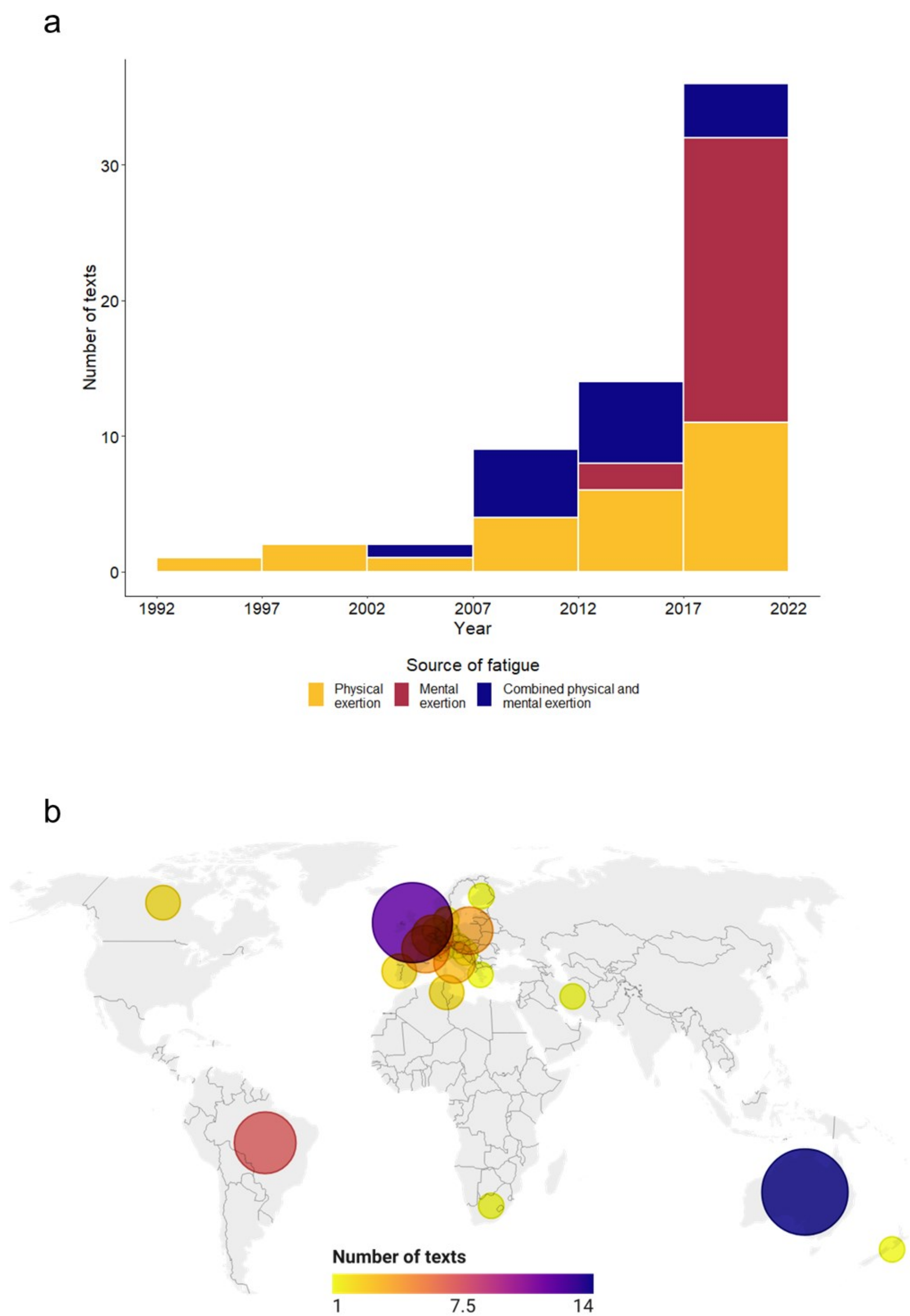

Figure 4.4. Distribution of the texts based on (a) their date of publication, grouped in periods of five years between 1992 – 2022; and (b) their country of origin.

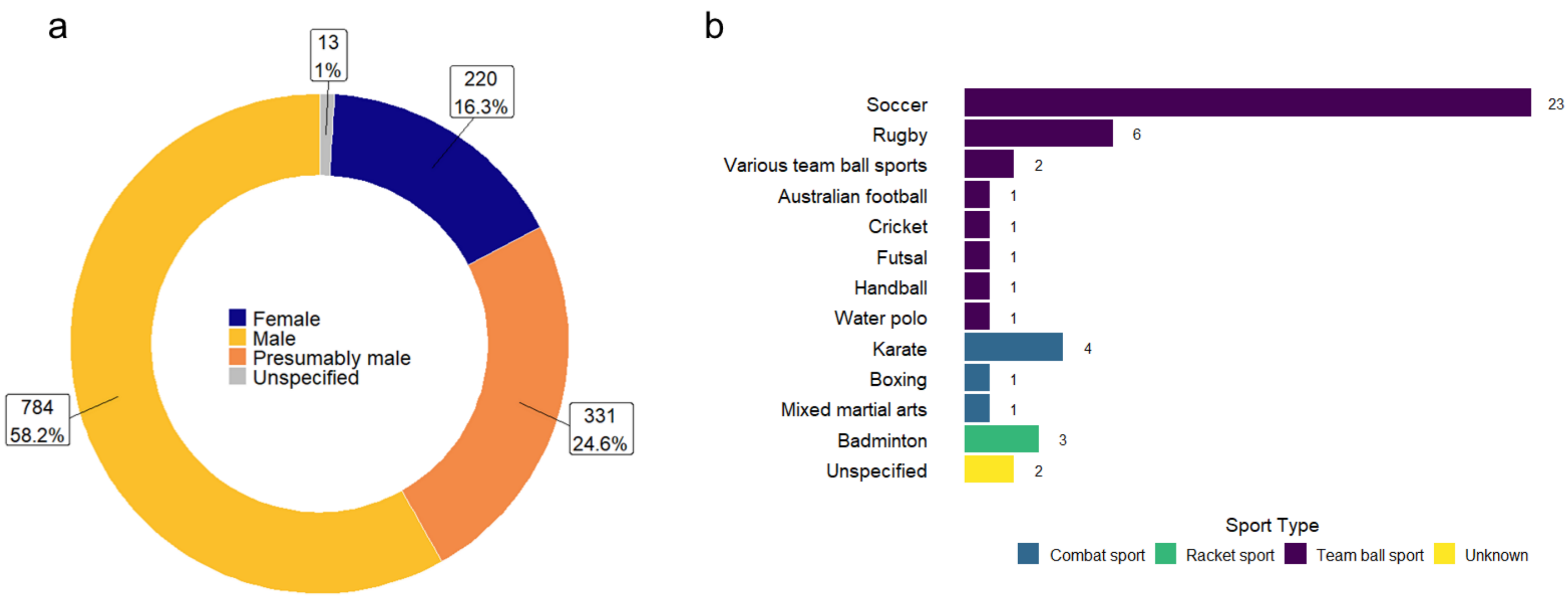

Figure 4.5. (a) Proportion of participants in the included experimental studies that were female, male, presumably male, or for whom sex was not specified. (b) The sports played by the participants and the number of experimental studies associated with each sport.

The sports played by the participants could be categorized as combat sports, racket sports, or team ball sports, with most of the studies focusing on team ball sport athletes (77%, Figure 4.5b). The number of studies involving soccer players (49%) was almost four times greater than the second most popular sport (rugby). Two studies had athletes from a mix of different team ball sports (Donnan et al., 2021; Duncan et al., 2015; Thomson et al., 2009) and two studies did not report the sport played by the athletes (Parkin & Walsh, 2017a; Parkin et al., 2017), but it could be reasonably deduced that participants were open-skill sport athletes based on contextual information and proposed applications described by the authors.

Reporting of the experience level of the athletes varied greatly, with authors indicating the years of experience and/or the current competition level, and/or describing athletes more generally (e.g., amateur/professional, elite) (Appendix A). Two studies did not provide any information regarding athlete experience level (Obmiński et al., 2017; Sepahvand et al., 2017).

4.4.2.2 Task inducing fatigue

In 51% of studies (n = 25), fatigue was induced by physical exertion, with 28% (n = 7) of the tasks considered sport-specific and 72% (n = 18) non-specific. The physical exertion involved incremental cycling or running tests to exhaustion (Bouhlel et al., 2014; Chmura & Jusiak, 1994; Chmura & Nazar, 2010; H. K. Faro et al., 2020; Finkenzeller et al., 2019; McMorris et al., 2000; Obmiński et al., 2017; Thomson et al., 2009), constant load cycling (Chmura et al., 1998), isolated muscle contractions (Del Percio et al., 2009; Zarrouk et al., 2016), repetitive sprints or maximal exercises (Bonnet, 2021; Browne, 2019; D. Coutinho et al., 2018; Donnan et al., 2021; Parkin & Walsh, 2017a; Parkin et al., 2017), cycles of running at different set paces (Alder et al., 2021; Mullen et al., 2019), and custom sport-specific designs (Alder et al., 2019; Barte et al., 2020; Goble & Christie, 2017; Redman et al., 2021; Royal et al., 2006; Russell, Benton, et al., 2011). In 27% of studies (n = 13), fatigue was induced by mental exertion, all of which used non-specific protocols: 10 used a Stroop test (Alder et al., 2021; Badin et al., 2016; D. Coutinho et al., 2018; Gantois et al., 2020; Kosack et al., 2020; Kunrath, Nakamura, et al., 2020; M. R. Smith et al., 2016; Trecroci et al., 2020; Van Cutsem et al., 2019; Weerakkody et al., 2021) and three used social media and/or video games (Fortes et al., 2020; Fortes, Gantois, et al., 2021; Fortes et al., 2019). In 22% of studies (n = 11) in which fatigue was induced by combined physical and mental exertion, 91% (n

= 10) featured a sport-specific task, either full-length matches (Bradley et al., 2014; Carling & Dupont, 2011; Kempton et al., 2013; Michailidis et al., 2018; Murphy et al., 2013; Nedelec & Dupont, 2019; Rampinini et al., 2009; Sepahvand et al., 2017; Skein et al., 2013) or small-sided games (Wilson et al., 2020), and the other one used a non-specific laboratory-based design in which the physical and mental parts were completed in sequence (Alder et al., 2021)..

The presence of fatigue was assessed via different methods. Of the 49 distinct designs identified in the 46 studies, in 35% of cases (n = 17), the manipulation check was decreased performance (e.g., increase in sprint times or Stroop test reaction times) and/or alteration in physiological parameters (e.g., increase in heart rate at the same workload). Tests of volitional exhaustion (n = 8), other previously validated fatigue protocols (n = 6), and full-length matches (n = 10) accounted for 49% of fatigue manipulation checks. Finally, 16% of the time (n = 8), the presence of fatigue was confirmed using exclusively self-reported measures (e.g., increased perception of effort over time to maintain performance, or increased perception of fatigue). Twelve percent (n = 6) of the designs, included, in addition to an objective manipulation check, self-reported measures that also confirmed the presence of fatigue; however, the majority (71%) either did not measure participant subjective ratings (n = 33) or did include subjective measures but did not report any increases in perception of effort to maintain performance in the fatiguing task (n = 2).

4.4.2.3 Perceptual-cognitive tasks

Of the 62 perceptual-cognitive tasks included in the 46 studies, 47% (n = 29) were sport-specific and 53% (n = 33) were non-specific tasks. Forty-eight percent (n = 14) of the sport-specific tasks were match play, and 52% (n = 15) were standardized tasks. Figure 4.6 displays how perceptual-cognitive task performance was affected by fatigue, based on how the authors of each study interpreted their results. When there was a negative effect, fatigue induced by physical exertion (Alder et al., 2021; Alder et al., 2019; Barte et al., 2020; Bonnet, 2021; Bouhlel et al., 2014; Browne, 2019; Chmura & Jusiak, 1994; Chmura et al., 1998; Chmura & Nazar, 2010; D. Coutinho et al., 2018; Del Percio et al., 2009; Donnan et al., 2021; H. K. Faro et al., 2020; Finkenzeller et al., 2019; Goble & Christie, 2017; McMorris et al., 2000; Mullen et al., 2019; Obmiński et al., 2017; Parkin & Walsh, 2017a; Parkin et al., 2017; Redman et al., 2021; Royal et al., 2006;

Russell, Benton, et al., 2011; Thomson et al., 2009; Zarrouk et al., 2016), mental exertion (Alder et al., 2021; Badin et al., 2016; D. Coutinho et al., 2018; Fortes et al., 2020; Fortes, Gantois, et al., 2021; Fortes et al., 2019; Gantois et al., 2020; Kosack et al., 2020; Kunrath, Nakamura, et al., 2020; M. R. Smith et al., 2016; Trecroci et al., 2020; Van Cutsem et al., 2019; Weerakkody et al., 2021), or a combination (Bradley et al., 2014; Carling & Dupont, 2011; Kempton et al., 2013; Michailidis et al., 2018; Murphy et al., 2013; Nedelec & Dupont, 2019; Rampinini et al., 2009; Sepahvand et al., 2017; Skein et al., 2013; Wilson et al., 2020) accounted for 41% (n = 11; 330 participants), 44% (n = 12; 198 participants), and 15% (n = 4; 53 participants), respectively, of instances. When there was no effect, fatigue was induced by physical exertion 74% of the time (n = 14; 268 participants), by mental exertion 16% of the time (n = 3; 53 participants), and by both physical and mental exertion made for the remaining 11% of instances (n = 2; 26 participants). When performance improvements occurred, it was after fatigue induced by physical exertion (78%, n = 7; 301 participants) or physical and mental exertion (22%, n = 2; 26 participants), but never after fatigue induced by mental exertion. Finally, there were seven studies (190 participants) for which the analyses involved other independent variables, making the main effect of fatigue uninterpretable: four involved fatigue induced by physical exertion and three by a combination of physical and mental exertion.

The most common requisite response was a micro-movement, required for 52% (n = 32) of the tasks. Twenty-three percent (n = 14) of tasks were assessed based on game performance, 18% (n = 11) required whole-body movement, and 8% (n = 5) required a verbal response. Figure 4.7 displays the effect of fatigue on the perceptual-cognitive task based on the requisite response. Of the 27 tasks for which there were negative effects of fatigue, 33% (n = 9; 304 participants) required micro-movements, 19% (n = 5; 69 participants) required whole-body movements, 11% (n = 3; 48 participants) required verbal response, and 37% (n = 10; 160 participants) tested game performance. For the 19 tasks where there was no change, 53% (n = 10; 196 participants) required micro-movements, 32% (n = 6; 115 participants) required whole-body movements, 16% (n = 3; 295 participants) tested game performance, and none required verbal response. There were 9 tasks for which there were positive outcomes after fatigue: 78% (n = 7; 303 participants) required micro-movements and 22% (n = 2; 24 participants) required verbal response. When the results were uninterpretable because the study manipulated variables additional to fatigue, all but one of these tasks involved micro-movements, with the other one measuring game performance. Only 19% (n = 12) of perceptual-cognitive tasks were performed simultaneously to the fatiguing task. Sixty-one percent (n = 38) were assessed in a pre-post or control vs. fatigued format, usually immediately after the fatiguing task – without the time delay being specifically reported – though in one case it was 45 minutes after the end of a match (Nedelec & Dupont, 2019). The remaining perceptual-cognitive tasks (19%, n = 12) were evaluated at more than two time points but never at the same time as when the fatiguing task was being performed.

4.4.3 Reviews, chapters, and other articles

Of the 18 texts that were not experimental studies, 67% (n = 12) were specifically focused on mental fatigue. Most (61%, n = 11) did not address one particular sport; of the seven that did, four focused on soccer, two on tennis, and one on “team sports”. Summaries presented in one review (Hornery et al., 2007) may have synthesized studies in which there was no spatial or temporal uncertainty (e.g., use of ball machines), but because of the links the authors drew to match play, it was still included. Main conclusions, relevant to the current review, are listed in Appendix B.

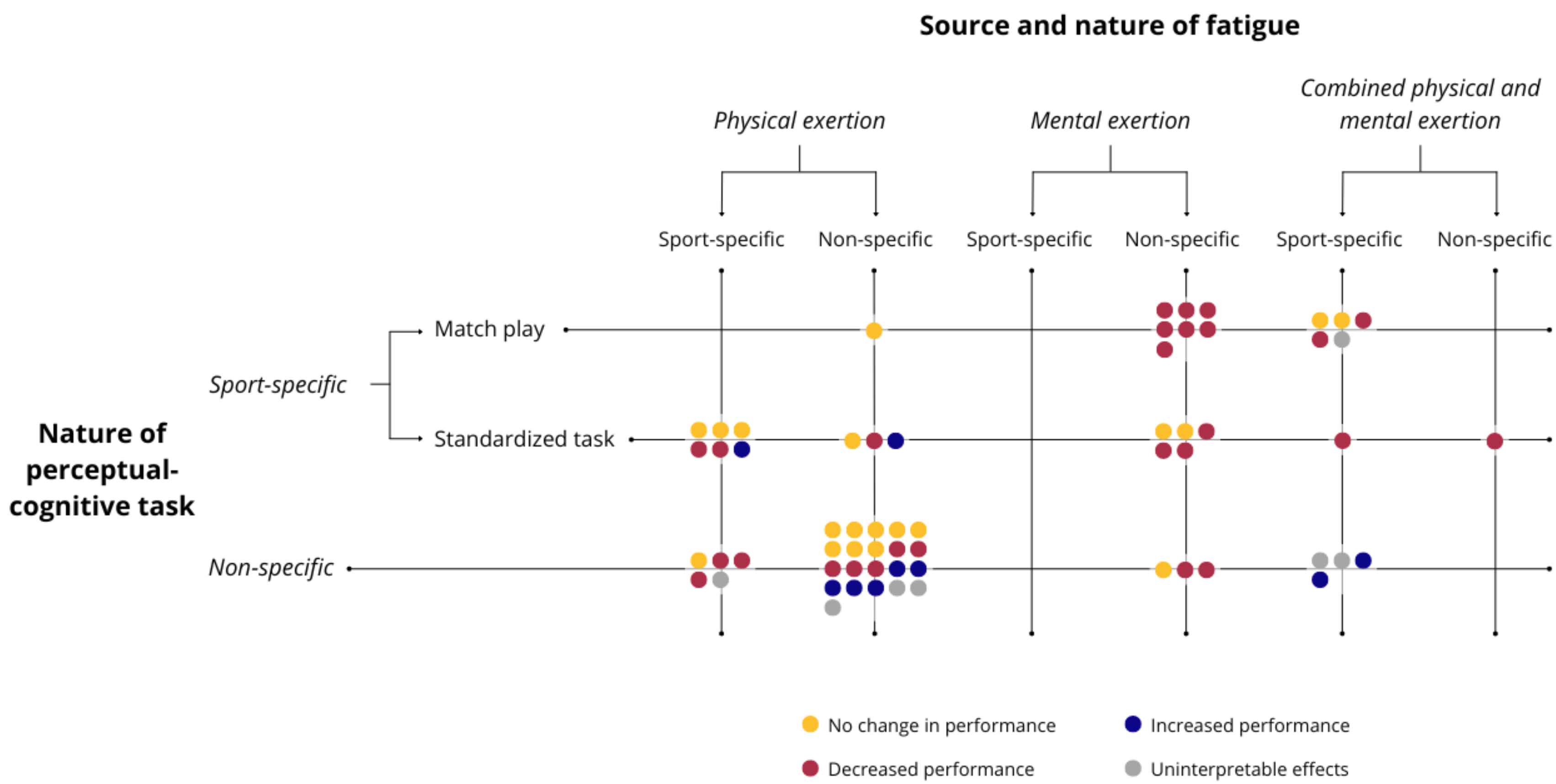

Figure 4.6. Effect of fatigue on perceptual-cognitive task performance based on the source of fatigue, the nature of the task inducing fatigue, and the nature of the perceptual-cognitive task.

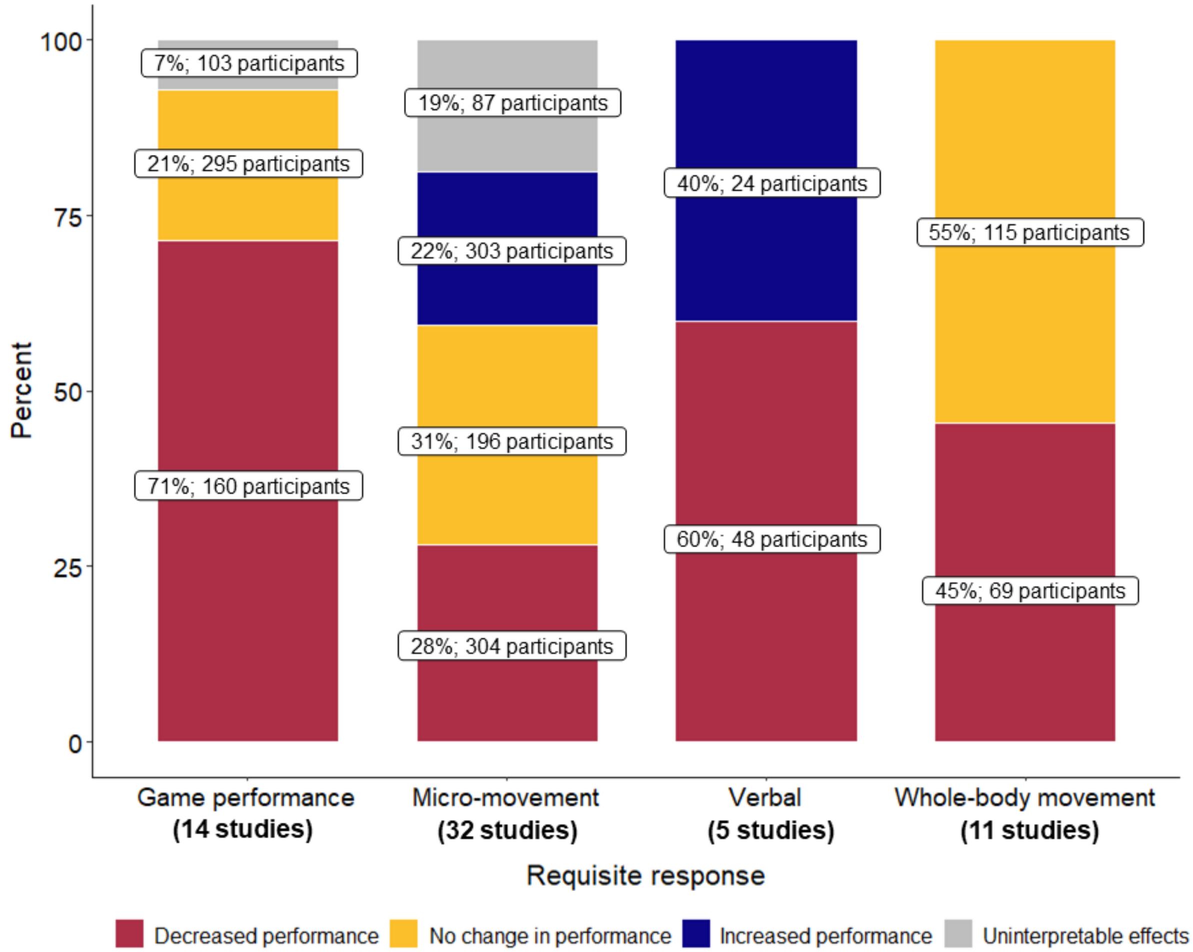

Figure 4.7. Proportion of negative, positive, no change, and uninterpretable effects of fatigue on performance based on the requisite response of the perceptual-cognitive task.

4.4.4 Discussion

This scoping review aimed to examine the current state of knowledge on the effects of fatigue on perceptual-cognitive performance among open-skill sport athletes. It focuses on the methods used to induce and confirm the presence of fatigue; the ways by which perceptual-cognitive performance was assessed; and the effects of fatigue on perceptual-cognitive task performance. Sixty-four articles were systematically identified, of which 46 were experimental studies and 18 were reviews, chapters, or other published articles.

4.4.5 General study characteristics

In sport and exercise research, following the seminal work by Marcora et al. (2009), initial interest in mental fatigue effects was primarily concentrated within endurance sport contexts, but has quickly increased among those involved in open-skill sports, with research involving fatigue induced by mental exertion accounting for much of the growth in the number of publications in this area (Figure 4.4a).

There was a notable underrepresentation of female participants, and the magnitude of this sex data gap was even greater than what has been reported previously for sport and exercise science research overall (Costello et al., 2014; Cowley et al., 2021). Consistent with findings from Cowley et al. (2021), studies involving only males rarely acknowledge this in the title: only two did. Moreover, 23% of studies likely involved only male athletes, but did not report the sex of participants. Such oversight in describing participants may indicate a more pernicious assumption of males being the "default" participant. Greater inclusion of female participants is imperative, particularly in light of demonstrated sex differences in fatigue (e.g., Hunter, 2016) as well as physiological (e.g., Sheel et al., 2004) and cognitive (e.g., Li, 2014) functions.

Characterization of participant caliber was used at the discretion of authors, making it difficult to compare between studies. This reinforces the importance of using a standardized classification system, such as the one proposed by McKay et al. (2022). Some researchers have found that elite athletes demonstrate superior perceptual-cognitive performance compared to lower-caliber counterparts (Mann et al., 2007), and being able to compare participant caliber across different studies could shed light on whether athlete expertise influences how, and/or the extent to which, perceptual-cognitive performance is affected by fatigue. Finally, although combat sports and racket sports were represented, in most of the studies, athletes were team ball sport players, and more specifically, soccer players. Kirkendall (2020) similarly reported that soccer publications represented 40% or more of all team sport publications since 2009, and this finding is understandable given the popularity of the sport worldwide.

4.4.6 Fatigue

4.4.6.1 Source of fatigue and nature of the fatiguing task

Half of all designs involved fatigue induced by physical exertion, of which most used tasks of non-specific nature. While there was a wide range of tasks used to induce fatigue through physical exertion, all the studies in which fatigue was induced by mental exertion involved non-specific tasks. Mental fatigue and its effects on game performance is becoming a growing area of interest, with some suggesting that it is a different construct from physical fatigue and should, like physical loads, be monitored and considered within a periodization plan (Russell, Jenkins, et al., 2020; Russell, Jenkins, Halson, Juliff, et al., 2022; Russell, Jenkins, Halson, & Kelly, 2022). It is therefore commendable that researchers are increasingly recognizing the relevance of measuring the impact of fatigue, resulting from mental exertion, on perceptual-cognitive performance. However, the ecological validity of using Stroop tests, in this context, has been questioned (Russell, Jenkins, Smith, et al., 2019; Smith et al., 2018). Although social media use and video games represent relevant real-life sources of fatigue, sequential task paradigms only provide insight on how performance may be affected when measured *after* an initial, isolated inducement of fatigue. In reality, fatigue can be induced by mental exertion occurring *during* gameplay, as evidenced by athletes reporting greater perceptions of mental fatigue after competitive matches (Russell, Jenkins, et al., 2020) and small-sided games (Badin et al., 2016; Sansone et al., 2020; Trecroci et al., 2020) compared to before. This suggests that the demands of match play themselves impose an important cognitive load, which could in turn impact perceptual-cognitive performance and accordingly, subsequent game performance. Though outside the scope of the current review, it should also be noted that athletes may accumulate fatigue from match-related, as well as non-match-related cognitive loads, such as media engagements, work/school commitments, etc., that may have negative effects on performance (Russell, Jenkins, Rynne, et al., 2019; Russell, Jenkins, Halson, & Kelly, 2022).

In addition to a lack of instances where fatigue was induced by mental exertion using a sport-specific task, few studies examined fatigue where the source was a combination of mental and physical exertion. In open-skill sports, athletes face physical and cognitive demands simultaneously, making it difficult and impractical to disentangle their separate contributions to the development of fatigue and the resulting decrements *during* sport performance. Evaluating how perceptual-cognitive performance is impacted by fatigue induced by a combination of physical and mental exertion is important, though it is not without methodological concerns. In the context of match play, which is by nature unpredictable and uncontrolled, there are individual differences in both physical and cognitive load, which have been highlighted by the wide range of subjective physical and mental fatigue values after a competitive match (Russell, Jenkins, et al., 2020), as well as in individual-specific decreases in physical action capabilities following small-sided games (Wilson et al., 2020). However, many standardized physical and mental fatigue protocols also do not take into consideration individual baseline differences in fitness or cognitive ability (O'Keeffe et al., 2020; Van Cutsem & Marcora, 2021), and individualized tests present a feasibility challenge, particularly given the availability of high-level athletes.

4.4.6.2 Manipulation check

When comparing fatigue induced by physical exertion to that induced by mental exertion, the variety of manipulation checks used mirrored the more diverse ways fatigue was induced by physical exertion. Additionally, while there were both objective behavioural and physiological manipulation checks for fatigue induced by physical exertion, the only objective validation methods for fatigue induced by mental exertion were behavioural (impaired Stroop test performance). The absence of other objective measures that have been used to assess mental workload, such as pupillometry (Sirois & Brisson, 2014), galvanic skin response (Nourbakhsh et al., 2012), and electroencephalography (Baumeister et al., 2008; Brownsberger et al., 2013), reflect the implementation challenges in dynamic, open-skill sport research environments.

All but one of the tasks that induced fatigue via both physical and mental exertion were full-length matches or used previously validated protocols. The exception was the study by (Wilson et al., 2020) in which fatigue resulting from small-sided games was confirmed by a decrease in physical action capabilities (decreased individual performance by at least 5% in one or more of: countermovement jump height, 5 m acceleration, 20 m sprint, or change-of-direction performance). This example highlights some of the limitations associated with characterizing fatigue as “mental” or “physical”. While the manipulation check was specific to declines in physical capacity, it would be misleading to label this as physical fatigue, because small-sided games also impose cognitive loads and the mental fatigue they engender (Badin et al., 2016; Sansone et al., 2020; Trecroci et al., 2020) may play an important role in subsequent decreases in perceptual-cognitive performance. Additionally, Browne (2019) reported increases in ratings of mental fatigue after a physically exerting protocol of repeated running sprints, further reinforcing that the "type" of fatigue is not exclusively determined by the type of exertion. For example, physical exertion still involves self-regulation requirements, which can impose important cognitive loads (Brick et al., 2016). Thus, although fatigue may result from physical and/or mental exertion, the existing categorizations of fatigue as *either* physical or mental can be limiting and confounding.

In two instances, perceived effort for a performance task was not different between fatigued and control groups (Gantois et al., 2020; Kosack et al., 2020), but in general, fatigue was associated with higher ratings of perceived effort for the performance task. For endurance performance, it is suggested that fatigue induced by physical and mental exertion both have negative impacts via increases in perception of effort (Pageaux & Lepers, 2016). Heightened fatigue-induced perceptions of effort are still potentially consequential for sport performance among open-skill sport athletes: gameplay often involves prolonged physical exertion and a need for sustained performance throughout a match/competition. Furthermore, the increase in perception of effort and decrease in motivation associated with mental fatigue is proposed to be related to accumulation of adenosine in the anterior cingulate cortex (ACC) (Martin et al., 2018; Pageaux et al., 2014), an area of the brain that is also critical for higher-order cognitive functions (Botvinick et al., 2004) required for perceptual-cognitive game performance. This, in conjunction with links established between perceived effort and movement choices and timing (Shadmehr et al., 2016; Wang et al., 2021) support the value of measuring self-reported perceptions of effort and fatigue to better understand the mechanisms by which fatigue affects performance. Most protocols did not involve subjective ratings of effort or fatigue. Fatigue is, however, a broad concept without a gold standard for measurement, and there are interindividual differences that can result in individual-specific manifestations of fatigue (Wilson et al., 2020). As such, multiple measures – both objective *and* self-reported – should be included.

4.4.7 Perceptual-cognitive task

4.4.7.1 Nature and requisite response of the perceptual-cognitive task

The exact task used and the measured performance outcomes differed greatly even among perceptual-cognitive tasks of the same nature. Non-specific tasks included the Paced Auditory Serial Test (Sepahvand et al., 2017), a visuomotor test (Van Cutsem et al., 2019), and various choice reaction time tests (e.g., Chmura et al. (1994)). Sport-specific tasks evaluated in a controlled context included video-based anticipation (e.g., Alder et al. (2019)) or decision-making tests (e.g., Royal et al. (2006)), reactive agility tests (e.g., Redman et al. (2021)), and choice reaction time-type tests requiring sport-specific movements (e.g., Russell, Benton, et al. (2011)). Though sport-specific tasks measured during match play all occurred during full-length or small-sided games, performance outcomes ranged from total number of balls lost (e.g., Bradley et al. (2014)) to passing decision making quality (e.g., Fortes et al. (2020)) to quality of attacking and defensive skill involvements (Kempton et al., 2013). Among the non-specific perceptual-cognitive tasks and the sport-specific ones performed as standardized tasks, participants were most often required to respond with a micromovement.

Overall, the different perceptual-cognitive tasks used varied greatly from one another due to the diverse combinations of the parameters of the task: the nature of task, the demands of the test, how it was presented, the response it required form the participant, as well as the timing of the task relative to when fatigue was induced (i.e., concurrently, pre- and post-, or at multiple intervals). These parameters may affect the degree to which the task is representative of sport-specific demands, potentially impacting how accurately performance changes reflect what the effects of fatigue would be on real sport performance, and consequently, how applicable research findings are to the field. Some perspectives highlight that athlete skill is context-dependent (Araújo et al., 2006; Mann et al., 2007), and how perceptual-cognitive performance is affected by physical load has been shown to differ based whether the task is sport-specific or not (Schapschroer, Lemez, et al., 2016). Open-skill sports take place in highly variable and dynamic situations, in which both the stimuli and athletes' actions are sport-specific. Ideally, research designs should reflect this, and the current literature highlights that this is a gap: even sport-specific perceptual-cognitive tasks involved requisite responses that lack sport fidelity (e.g., mouse click, verbal response). In the context of how sport performance-induced fatigue affects perceptual-cognitive skills, on top of the requisite response, the timing of the perceptual-cognitive task relative to the fatigue protocol adds another layer: to be more representative of the perceptual-cognitive demands during an ongoing match, the task should occur simultaneous to the fatigue protocol.

4.4.8 Fatigue effects on perceptual-cognitive performance

The heterogeneity of all these perceptual-cognitive task parameters, combined with the various different methods by which fatigue was induced, contributes to the different consequences of fatigue on performance (Figure 4.6). When fatigue was induced by physical exertion or by a combination of physical and mental exertion, the resulting impact on perceptual-cognitive performance was equivocal, with some studies reporting negative effects but others documenting improved performance or no differences at all.

Though enhanced performance after fatigue may be unexpected, single-session exercise has previously also been shown to have positive effects on cognitive performance, with the exercise intensity, type and timing of the perceptual-cognitive performance, and participant fitness playing moderating roles (Chang et al., 2012; Schapschroer, Lemez, et al., 2016). Although only studies involving exercise *that induced fatigue* were included in the current review, it is possible that these variables could also help explain performance improvements after fatigue induced by physical or combined physical and mental exertion. Depending on the intensity and duration of physical exercise, key brain areas such as the prefrontal cortex, sensory cortices, and associated areas may be activated, due to increased levels of brain catecholamines, and facilitate perception and sensation (Audiffren, 2016; McMorris et al., 2016). However, if increases in catecholamines are excessive and/or the secretion of hypothalamus-pituitary-adrenal axis hormones is initiated, this may trigger overarousal and impaired cognitive functioning (see McMorris et al. (2016) for a detailed account). Decreases in brain oxygenation in prefrontal regions at maximal, but not low or moderate, exercise intensities have also been associated with declines in cognitive task performance during exercise (Audiffren, 2016). Thus, the differing durations, modalities, intensities, and energetic demands of the physical exertion protocols, as well as the different ways fatigue was validated, may have resulted in varying degrees of metabolic, neurochemical, and hormonal changes, and consequently, varying effects on perceptual-cognitive performance. This hypothesis should, however, be tested directly. In contrast, there were more uniform negative effects observed for fatigue induced by mental exertion. The consistency of these results may reflect the homogeneity of how fatigue was induced by mental exertion: in almost all cases, it involved completing 30-60 min of a Stroop task. This type of prolonged cognitive task is thought to cause adenosine build up in the ACC, which, as described above, could negatively impact executive functioning and result in performance decrements. An in-depth discussion of the mechanisms associated with fatigue induced by physical and mental exertion is outside the scope of the current review, and work is still being conducted to understand the interaction of psychological factors, such as motivation, on performance.

Concerning the parameters of the perceptual-cognitive task, Travassos et al. (2013) demonstrated that the response modality, as well as the means of stimulus presentation, affect the magnitude of performance differences between experts and novices on decision-making tests. Schapschroer, Lemez, et al. (2016) also found that how physical exercise affected perceptual-cognitive performance was related to how sport-specific both were, and different neurochemical mechanisms underpinning task-dependent effects of exercise on cognitive performance have been described (McMorris et al., 2016). It thus seems reasonable to suggest that the parameters of the perceptual-cognitive task, in addition to the method of fatigue inducement, may also influence the degree to which performance is sensitive to the effects of fatigue. This is exemplified by the study by Van Cutsem et al. (2019) in which they concluded that a visuomotor task that required whole-body movements was more susceptible to the effects of mental fatigue than a traditional cognitive task that required micro-movements. In general, there was the most amount of ambiguity for tasks requiring micro-movement responses and more consistent effects when the task required game performance (Figure 4.7).

As a general note, participants should receive adequate familiarization with the performance task and, whenever possible, the reliability of the task or measures should be confirmed in order to bolster confidence that changes in performance can be truly attributable to the variable of interest (e.g., fatigue). Without these verifications, results demonstrating no change or positive effects following fatigue could actually represent learning effects, particularly when studies use within-subjects pre-post designs. It should be noted that reliability is equally important to consider when studies report negative effects, so as to be able to link performance decrements to fatigue effects and not just the inherent variability associated with the task. Finally, when considering the dissonance between the equivocal results of this study and subjective claims of fatigue-induced decreases in decision-making quality or sport performance, we should also recognize that the latter are often made in reference to mistakes made during match play, and frequently in a context where the outcome of the mistake had decisive consequences. This is coherent with our tendency to remember emotionally affective events – particularly negative ones – more than neutral ones (Ochsner, 2000). However, this memory bias for emotionally powerful situations coincides with the fact that the factors that magnify the intensity of the moment may also themselves affect perceptual-cognitive performance. For instance, pressure or high stakes (e.g., playing against an important rival opponent or during a championship final match) can engender feelings of anxiety for an athlete, which in turn can impact the way they take in, interpret, and use the information around them, as well as affect their movement execution (Nieuwenhuys & Oudejans, 2017; Wilson, 2008). Furthermore, besides independently influencing perceptual-cognitive ability, certain features of significant match situations (e.g., crowd presence, unfamiliar opponents, performance pressure) impose additional cognitive loads for the athlete (Russell, Kelly, et al., 2020), interacting with the physical and mental exertion already inherent to the sport to potentially accelerate the development of fatigue. Thus, pressure/anxiety, which are core elements of competitive sport, would be meaningful elements to consider and could help elucidate a broader and more complete understanding of changes in perceptual-cognitive performance that occur during matches after prolonged physical and/or mental exertion.

4.4.9 Reviews, chapters, and other articles

Twelve of the 18 reviews, chapters, and other published articles focused on fatigue induced by mental exertion, highlighting the accelerating interest in how “mental fatigue” affects sport performance. Authors indicated that when inducing fatigue using a cognitive task, the task demand and associated engagement in the task (Aitken & MacMahon, 2019; Brown et al., 2020; Van Cutsem & Marcora, 2021) should be considered, rather than exclusively the duration of the task. Others also identified ecological validity challenges with inducing and assessing the effects of mental fatigue (Russell, Benton, et al., 2011; Thompson et al., 2019). A common theme was the linking of the negative effects of fatigue induced by prior mental exertion with decreased self-control/self-regulation (Aitken & MacMahon, 2019; Brown et al., 2020; Englert et al., 2021; Russell, Jenkins, Rynne, et al., 2019; Russell, Kelly, et al., 2020). Schmit and Brisswalter (2020), with their dynamical model of exercise-related fatigue, proposed that self-regulation failure is also the cause of impaired cognitive performance during prolonged physical exertion.

While many of the secondary sources generally supported the notion of fatigue impairing athletes' perceptual-cognitive performance (e.g., "decision making", "tactical performance", "psychomotor performance") (Aitken & MacMahon, 2019; Brown et al., 2020; Englert et al., 2021; Habay et al., 2021; Jukic et al., 2011; Kunrath, Cardoso, et al., 2020; Pageaux & Lepers, 2018; Russell & Kingsley, 2011b; Russell, Jenkins, Rynne, et al., 2019; Russell, Jenkins, Smith, et al., 2019; Russell, Kelly, et al., 2020; Thompson et al., 2019; Van Cutsem & Marcora, 2021), and though this may feel like an intuitive result easily supportable by anecdotal accounts, based on the available literature, it does not appear that fatigue invariably has negative impacts on perceptual-cognitive or sports performance. Many of the authors acknowledged there are nuances to the relationship between fatigue and performance, with differing effects based on the task (Brown et al., 2020; Habay et al., 2021; Russell, Benton, et al., 2011; Van Cutsem & Marcora, 2021), while others described ambiguous or even positive changes to performance when fatigued (Clemente et al., 2021; Knicker et al., 2011; Reid & Duffield, 2014). In addition to heterogeneity in study designs and in the tasks used to induce fatigue and to assess performance, other interacting factors, like motivation (Aitken & MacMahon, 2019; Brown et al., 2020; Reid & Duffield, 2014), may contribute to this conflicting empirical evidence.

4.4.10 Strengths and limitations

This scoping review is the first to aggregate the literature on the effects of fatigue on perceptual-cognitive performance among open-skill sport athletes. In existing reviews about the effects of fatigue on sport performance, authors often considered just one facet of fatigue (e.g., "mental fatigue"). By including articles in which fatigue was induced by physical and/or mental exertion, the current review aimed to take a broader approach to the fatigue phenomenon and its impact on performance. Having a predefined set of accepted validation criteria of fatigue, rather than relying on each article's use of fatigue, was also important in preserving the focus of this scoping review. Similarly, a clear operationalization and precise inclusion criteria for perceptual-cognitive performance tasks ensured consistency in the article selection process. Finally, although most reviews only consider published original research, in accordance with recommendations by the JBI (Peters et al., 2020), we also included secondary literature and unpublished primary literature (theses).

One limitation is that some articles did not primarily focus on fatigue effects, and were aimed instead at understanding the effect of Ramadan fasting (Bouhlel et al., 2014; Zarrouk et al., 2016), sex differences (Bradley et al., 2014), heat exposure (Donnan et al., 2021), alcohol ingestion (Murphy et al., 2013), pre-match stress (Sepahvand et al., 2017), or sleep deprivation (Skein et al., 2013). While the control conditions were examined for these cases, because the statistical analyses were designed with the primary (non-fatigue-related) research objective in mind, interpretations of the effects of fatigue were not always possible. It should also be noted that adhering to the sport categorizations in current use (Table 1) could have contributed to the ambiguity of the results: this review included studies in which participants were combat, racket, and team ball sport athletes. While all do require perceptual-cognitive skills, there are still marked differences between the demands of returning a tennis serve and wrestling your competitor or keeping track of multiple teammates and opponents – in addition to important differences in sport physiological demands and, presumably, fatigue tolerance. Accordingly, it may not be appropriate to evaluate their perceptual-cognitive performance under fatigue as a single group. Concomitantly, this method of classifying sports may be limiting in diminishing the major role perceptual-cognitive ability plays in some sports categorized as closed-skill or static, such as short-track speed skating or track cycling.

4.4.11 Conclusions and recommendations

This scoping review identified 64 texts that examined or discussed the effects of fatigue on perceptual-cognitive performance among open-skill sport athletes. Fatigue was induced by physical, mental, or a combination of physical and mental exertion, most often in non-specific ways. Perceptual-cognitive performance was measured by using sport-specific tasks – via match play or standardized tasks – or by using non-specific tasks. These tasks varied widely in the requisite response and the timing relative to when fatigue was induced. Findings from the included studies indicated that fatigue induced by mental exertion before the perceptual-cognitive task had negative effects on perceptual-cognitive performance. When fatigue was induced by physical exertion, or by a combination of physical and mental exertion, outcomes were more ambiguous: negative, positive, and no effects on performance were all observed. The variation in these results may be associated with the greater heterogeneity of the nature of the fatigue and of how it was induced when it was by physical exertion or combined physical and mental exertion, compared to the more consistent ways in which fatigue due to mental exertion was induced. Perceptual-cognitive tasks that required responses more similar to sport-specific demands were potentially more sensitive to the negative effects of fatigue compared to non-specific tasks, but this hypothesis would require further confirmation.

In synthesizing the available literature, several gaps and recommendations for future research were identified. When describing participants, authors should explicitly report participants' sex, age, and sport expertise. To contextualize their sport experience more clearly, they should also provide information pertaining to participant fitness and caliber, as well as nationality and sport-related success. Guidelines such as those proposed by McAuley et al. (2022) and McKay et al. (2022) offer in-depth considerations for characterizing participants. There remains a pronounced underrepresentation of female participants overall, and there are few studies that investigate sex differences. As previously noted, a Stroop test to induce fatigue is limited in the extent to which it represents how fatigue occurs due to the cognitive demands of gameplay (Thompson et al., 2019). Researchers are beginning to investigate more ecologically valid means of imposing cognitive loads to induce fatigue (Bian et al., 2022), and this is an area that should continue to be explored. Notably, while there is value in measuring self-reported physical fatigue and mental fatigue for monitoring physical and mental load (Russell, Jenkins, Halson, Juliff, et al., 2022), during match play, physical and mental loads occur simultaneously and interact in their contributions to fatigue and fatigue-related changes to performance. Accordingly, it would be highly pertinent, as well as most representative of open-skill sport demands, for researchers to employ fatiguing protocols that involve both physical and mental exertion, such as small-sided games or dual-task protocols. Assessing perceptual-cognitive performance at multiple intervals over time, ideally during the fatiguing protocol, in addition to doing pre- and post- measures, would similarly increase the applicability of the findings. Subjective measures, including ratings of fatigue and perceived effort, should be included to complement objective measures of performance to provide a more complete perspective of the development and the perception of fatigue. As fatigue manifests both objectively and subjectively, the addition of subjective measures is essential to fully capture the fatigue phenomenon. When possible, researchers should aim to have various measures of the objective and subjective manifestation of fatigue to validate its presence. On the field, systematic and/or standardized measures can be unfeasible due to time, financial, or personnel constraints. In such situations, psychophysical scales to measure perception of fatigue remain easily implementable tools. Finally, as one of the underlying goals of this area of research is ultimately to understand the deterioration of perceptual-cognitive performance over time during match play, study designs should recognize the importance of performance context by beginning to investigate the roles of other stressors, such as psychosocial stressors (e.g., pressure, emotional regulation) and environmental stressors (e.g., heat). As they are both are highly relevant to the competition context and independently associated with negative effects on cognitive function, they may have important interactions with prolonged physical and mental exertion.

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Declaration of interest: The authors declare that they have no conflicts of interest.

Data availability: All data generated or analyzed during this study are included in this published article and its supplementary information files.

4.5 Supplementary material: Appendix A

Table 4.2. Characteristics and relevant main findings of experimental studies, organized by the source (first level) and nature (second level) of the fatigue. Sample experience is listed as described by the authors and fatigue effects are based on authors' interpretations.

Reference	Sample	Fatiguing protocol	Manipulation check	Perceptual-cognitive task	Fatigue effects on performance	Fatigue effects on subjective measures
Fatigue from physical exertion						
Sport-specific						
Alder et al. (2019)	13 badminton players Age: 24.1 ± 5.5 y Experience: 10 ± 3.9 y; 2 Commonwealth, 2 international, 6 national, 2 county-level competitors	48 repetitions of a badminton exercise protocol: 1 min of intense ghosting at allocated targets on the badminton court, with directions given by the investigator; and an adapted agility course with sprinting, side-stepping, and lunges	Increase in heart rate without an increase to task demands	Video-based anticipation test with 6 response options performed after each exercise protocol. Response: verbal and whole-body movement	Increase in accuracy for block 3 and 4 of the total 6, followed by a decrease such that the last block was worse and no better than chance performance	Tendency for higher RSME later in the test
Barte et al. (2020)	30 male soccer players Age: 20.3 ± 3.3 y Experience: competitive amateurs competing inter-regionally	High-intensity intermittent running protocol of 2 x 47 min separated by a 13-min halftime. Each half had 5 blocks of walking, sprinting, jogging, striding, moving sideward, passive recovery. The first four blocks of each	Validated fatigue protocol (Russell, Rees, et al., 2011)	Interception test after the exercise or control protocol in which a ball release system shot ground passes at different pre-set velocities and players had to decide if they could intercept the ball before it reached Cone A and then	No differences for number of interception attempts or success rate of interceptions	Decreased motivation to intercept after compared to before the fatigue protocol

		half also had passing/shooting		do so, or otherwise run to cone B to take a defensive position Response: whole-body movement	
Goble and Christie (2017)	15 male cricket players Age: 17 ± 0.92 y Experience: amateur	BATEX simulation with six stages of five overs. Each over involved 6 deliveries fed by a bowling machine and a mandatory number of shuttles required that could be completed in any order. Stages 1, 3, 5 were self-paced running, while 2, 4, 6 were max sprints	Increase in sprint times and increase in heart rate without an increase to task demands	Groton maze learning test at baseline and before, throughout (after stages 1, 3, 5) and after the exercise protocol. Response: micro-movement	Faster (more moves per second) but more errors
Goble and Christie (2017)	15 male cricket players Age: 17 ± 0.92 y Experience: amateur	BATEX simulation with six stages of five overs. Each over involved 6 deliveries fed by a bowling machine and a mandatory number of shuttles required that could be completed in any order. Stages 1, 3, 5 were self-paced running, while 2, 4, 6 were max sprints	Increase in sprint times and increase in heart rate without an increase to task demands	One-card learning test at baseline and before, throughout (after stages 1, 3, 5) and after the exercise protocol. Participants clicked the card if it had previously been seen. Response: micro-movement	Initial increase followed by a decrease in accuracy; faster response time
Goble and Christie (2017)	15 male cricket players Age: 17 ± 0.92 Experience: amateur	BATEX simulation with six stages of five overs. Each over involved 6 deliveries fed by a	Increase in sprint times and increase in heart rate without an increase to task demands	One-back card test at baseline and before, throughout (after stages 1, 3, 5) and after the	Decrease in accuracy

		bowling machine and a mandatory number of shuttles required that could be completed in any order. Stages 1, 3, 5 were self-paced running, while 2, 4, 6 were max sprints		exercise protocol. Participants determined if the card was the same or different from the previous card. Response: micro-movement	
Goble and Christie (2017)	15 male cricket players Age: 17 ± 0.92 Experience: amateur	BATEX simulation with six stages of five overs. Each over involved 6 deliveries fed by a bowling machine and a mandatory number of shuttles required that could be completed in any order. Stages 1, 3, 5 were self-paced running, while 2, 4, 6 were max sprints	Increase in sprint times and increase in heart rate without an increase to task demands	Choice reaction test at baseline and before, throughout (after stages 1, 3, 5) and after the exercise protocol. Participants right- or left-clicked depending on if a card flipped over was red or black. Response: micro-movement	Increase in reaction time
Kempton et al. (2013)	17 Rugby League players (6 National Rugby League; 11 National Youth Competition) Age: 22.3 ± 2.5 y (NRL); 18 ± 1.2 y (NYC) Experience: Professional club teams	Full-length competitive match	Full-length match	Technical skill performance (attempted tackle, pass receive, kick receive, pass, "dummy-half" pass, ball carry, kick (attacking), kick (territory)) from 22 NRL and 23 NYC matches rated by coaches from a scale of 0-5. Response: sport performance	Lower average skill rating in later (70-75 min, 75-80 min) compared to earlier periods (0-5 min, 40-45 min and 30-35 min)

Mullen et al. (2019)	20 male Rugby League players Age: 21.4 ± 2.1 y Experience: varsity-level	Rugby league movement simulation protocol for interchanged players (RLMSP-i): two 23-min bouts with 20 min passive recovery between. Each quartile of each bout required an assortment of movements, the order of which was randomized	Decrease in maximal knee extension strength	Stroop task (iPad) performed before and after each bout until achieving 80 correct trials. Response: micro-movement	Uninterpretable
Redman et al. (2021)	20 male Rugby League players Age: 15.9 ± 0.9 y Experience: Elite Junior	Match simulation protocol: 23 cycles of movement patterns involving physical contact (tackling), high-intensity and very high-intensity movement on a 20m course, repeated twice	Decrease in countermovement jump height	Reactive agility test performed before, halfway through, and after the match simulation, in which players sprinted forward and had to react to a human tester's cue that would dictate the player's direction change. Response: whole-body movement	No change in decision time
Redman et al. (2021)	20 male Rugby League players Age: 15.9 ± 0.9 y Experience: Elite Junior	Match simulation protocol: 23 cycles of movement patterns involving physical contact (tackling), high-intensity and very high-intensity movement on a 20m course, repeated twice	Decrease in countermovement jump height	Video-based decision-making test performed before, halfway through, and after the match simulation, requiring players to circle, on a paper copy of a screenshot of the last frame, the player they predicted would	No change in accuracy

				receive the ball. Response: Pen and paper		
Royal et al. (2006)	14 male water polo players Age: 17.2 ± 0.5 y Experience: Junior Elite	Four sets of 8 repetitions of a water polo-specific drill at max effort, involving swimming with ball, baulking, shooting, sprinting within a 5x5m area. Each subsequent set had shorter recovery periods between the reps: 80s, then 40s, 20s, 10s)	Increases in heart rate and blood lactate without an increase to task demands, and increase in time needed to complete the drill	Video-based decision-making test with 5 response options performed before and after each set. Response: verbal, while baulking in the water	Better accuracy at very high exertion compared to light, moderate, and high intensity. Pre-test accuracy was higher than at light and moderate	
Russell, Benton, et al. (2011)	15 male soccer players Age: 18.1 ± 0.9 y Experience: member of Youth English Championship team for at least 12 months	Soccer match simulation: 14 repetitions separated by a 15-min halftime of 4.5 min blocks consisting of walking, sprinting or dribbling, jogging, backward jogging, striding	Decrease in sprint speed	Shooting (before and after each half of the exercise protocol) and passing (after every 4.5-min block of exercise) skill tests in which players aimed a ball towards the center of a target of a randomly determined target. Response: whole-body movement	Decrease in shooting precision after exercise. No change to shooting success, passing precision, or passing accuracy	
Non-specific						
Alder et al. (2021)	16 male soccer players Age: 22.4 ± 2.5 y Experience: 14 ± 3.6 y; semi-pro UK teams	Drust running protocol (40 min of 15 blocks of jogging, sprinting, walking)	Validated fatigue protocol (Drust et al., 2000)	Video-based anticipation test with 3 response options performed before and after the	Decrease in accuracy compared to baseline measures	Higher RPE than for the mental load condition

				fatigue protocol. Response: verbal		
Bonnet (2021)	37 male handball players Age: 25.2 ± 6.19 y Experience: regional-level (6th or 7th French division)	4 min of burpee Tabata	Decrease in number of repetitions of burpees per 20 sec interval	Two-choice reaction time test performed before and after the fatiguing protocol. Response: micro-movement	Faster reaction time	
Bonnet (2021)	37 male handball players Age: 25.2 ± 6.19 y Experience: regional-level (6th or 7th French division)	4 min of burpee Tabata	Decrease in number of repetitions of burpees per 20 sec interval	Image-based decision-making test with 2 response options performed before and after the fatiguing protocol. Response: micro-movement	More accurate and faster performance	
Bouhlel et al. (2014)	10 male karate athletes Age: 18.5 ± 0.5 y Experience: moderately trained	Incremental cycling test until achieving at least two VO_2max criteria	Volitional exhaustion	Four-choice reaction time test performed before and after the incremental test. Response: micro-movement	Uninterpretable	
Browne (2019)	24 male Rugby Union players Age 21.4 ± 1.7 y Experience: > 6 y competitively; top 5 divisions of English Rugby Union	20 x 20 m sprints with 20 s active recovery	Validated fatigue protocol (repeated sprints, e.g., (Collins et al., 2018))	Four-choice reaction time test performed before and after the fatiguing protocol. Response: micro-movement	No change in accuracy or response time	Uninterpretable
Browne (2019)	24 male Rugby Union players Age 21.4 ± 1.7 Experience: > 6 y competitively; top 5	20 x 20 m sprints with 20 s active recovery	Validated fatigue protocol (repeated sprints, e.g., (Collins et al., 2018))	Stroop test with four colours performed before and after the fatiguing protocol.	Faster response time for congruent trials	Uninterpretable

	divisions of English Rugby Union			Response: micro-movement		
Browne (2019)	24 male Rugby Union players Age 21.4 ± 1.7 Experience: > 6 y competitively; top 5 divisions of English Rugby Union	20 x 20 m sprints with 20 s active recovery	Validated fatigue protocol (repeated sprints, e.g., (Collins et al., 2018))	Computerized Corsi block test performed before and after the fatiguing protocol	No change in span score	Uninterpretable
Chmura et al. (1994)	22 male soccer players Age: 21.3 ± 0.2 y Experience: professional (Polish 3rd league team)	Incremental cycling test to volitional exhaustion with 1 min rest between each 3-min stage	Volitional exhaustion	Choice-reaction time test with 2 response options, and 4 types of stimuli (2 of which were to be ignored) performed before the incremental test and during the last 2 min of each stage. Response: micro-movement	Gradual decrease in reaction time until 76% of VO_2max, after which it then rapidly increased	
(Chmura et al., 1998)	8 male soccer players Age: 24.8 ± 1.4 y Experience: professional (Polish 3rd league team)	20 min constant load cycling at 10% above lactate threshold	Increase in blood lactate with no plateauing and without an increase to task demands	Choice-reaction time test with 2 response options, and 4 types of stimuli (2 of which were to be ignored) performed before the incremental test and every 5 min throughout exercise. Response: micro-movement	Linear decrease in reaction time	
Chmura and Nazar (2010)	13 male soccer players Age: 23.2 ± 1 y Experience: professional	Incremental treadmill test to volitional exhaustion	Volitional exhaustion	Choice-reaction time test with 2 response options, and 4 types of stimuli (2 of which	Gradual decrease in reaction time until ~70-80% of maximal aerobic workload where it	

				were to be ignored) performed before the incremental test and during the last 2 min of each stage. Response: micro-movement	increased until 100% workload. Errors, though minimal, only occurred at maximal running speed
D. Coutinho et al. (2018)	10 soccer players Age: 13.7 ± 0.5 y Experience: 6.1 ± 0.9 y; regional soccer academy	6 x 20 m repeated COD task lasting ~4 min, involving four 100 deg directional changes every 4 m and 25 s of active recovery between bouts	Validated fatigue protocol (repeated sprints, e.g., (Collins et al., 2018)); increase in RPE without an increase to task demands	3 x 6 min small-sided games (5v5, plus keeper) performed after the fatigue protocol. Response: sport performance	Decrease in distance between dyads, increase in APEn distance dyads, decrease in team stretch index, decrease in time spent synchronized in longitudinal displacements
Del Percio et al. (2009)	14 karate athletes (6 female) Age: 24.1 ± 1.3 y Experience: elite (Italian national team)	Isometric contractions of the right quad for 60 minutes alternating 6 s at 50% MVC and 4 s of rest	Inability to continue task	Posner's test performed before and after the fatiguing protocol: 2-choice reaction test in which the position of the stimuli varied. Response: micro-movement	Uninterpretable
Donnan et al. (2021)	12 male team sports athletes (soccer, rugby, basketball, futsal) Age: 21.4 ± 3.3 Experience: 11.7 ± 4.2 y	Cycling Intermittent Sprint Protocol (CISP): 40 repetitions of a 2-min cycling period, each consisting of a 5-s all-out sprint, 105 s of active recovery, then 10 s of passive rest. 15-min of passive recovery after the first 20 repetitions.	Increase in RPE without an increase to task demands	Computerized Stroop test with four colours performed during the active recovery periods of the 2nd, 7th, 12th, and 17th blocks of each half of the CISP. Response: micro-movement	Decrease in accuracy for incongruent trials in the 2nd and 3rd quarters compared to the 1st

H. K. Faro et al. (2020)	3 mixed martial arts athletes Age: 29, 31, 31 y Experience: elite (ranked top-3 worldwide in their categories)	Incremental cycling test to volitional exhaustion	Volitional exhaustion	Computerized Stroop test with four colours and switch trials performed before and after the incremental test. Response: micro-movement	Decrease in reaction time
Finkenzeller et al. (2019)	178 soccer players (87 female) Age: 15.07 ± 0.98 y Experience: Youth National Austrian team	Incremental treadmill test to volitional exhaustion	Volitional exhaustion	Vienna Determination Test: choice reaction time test with responses using hands or feet performed before and after the incremental test. Response: Micro-movement	Decrease in reaction time, decrease in accuracy (strikers only), increase in number of correct responses
Finkenzeller et al. (2019)	20 female soccer players Age: 14.71 ± 0.56 y until 19.5 ± 1.2 y (longitudinal) Experience: Senior National Austrian team	Incremental treadmill test to volitional exhaustion	Volitional exhaustion	Vienna Determination Test: choice reaction time test with responses using hands or feet performed before and after the incremental test. Response: Micro-movement	Uninterpretable
McMorris et al. (2000)	12 male soccer players Age: 20 ± 2 y Experience: college-level	Incremental cycling test to volitional exhaustion	Volitional exhaustion	Video-based decision-making test with 3 response options performed before and after the incremental test. Response: verbal and simultaneous	No change in reaction time or motor performance

				whole-body movement	
Obmiński et al. (2017)	14 karate athletes Age: unspecified Experience: unspecified	Incremental cycling test until volitional exhaustion	Volitional exhaustion	Ten-choice reaction test performed before and after the incremental test. Response: micro-movement	No differences for number of correct responses
Obmiński et al. (2017)	14 karate athletes Age: unspecified Experience: unspecified	Incremental cycling test until volitional exhaustion	Volitional exhaustion	Go/No-Go test performed before and after the incremental test. Response: micro-movement	No difference in response time or number of errors
Parkin and Walsh (2017a)	31 athletes (15 female) Age: 20.05 y (range 18-27) Experience: sub-elite; training for about 12 y; participating in centralized national program training for Olympics in 4-8 y; classified as competitive-elite and semi-elite based on Swann et al. (2015)	6 repetitions of 30 s all-out cycling alternating with 30 s rest	Validated fatigue protocol (repeated sprints, e.g., (Collins et al., 2018))	Cambridge Gambling Task performed at rest and after a set of the 6 sprints. Response: micro-movement	Less deliberation time, fewer errors, increased risk-taking and reduced risk adjustment
Parkin and Walsh (2017a)	31 athletes (15 female) Age: 20.05 y (range 18-27 y) Experience: sub-elite; training for about 12 y; participating in centralized national	6 repetitions of 30 s all-out cycling alternating with 30 s rest	Validated fatigue protocol (repeated sprints, e.g., (Collins et al., 2018))	Stop Signal Reaction Time Test performed at rest and after a set of the 6 sprints. Response: micro-movement	No differences in response time or response inhibition processes

	program training for Olympics in 4-8 y; classified as competitive-elite and semi-elite based on Swann et al. (2015)				
Parkin et al. (2017)	23 athletes (11 female) Age: 28.25 y (range = 23-36 y) Experience: world-class elite; training for about 20 y; international championship experience; classified as world-class and successful-elite based on Swann et al. (2015)	8 repetitions of 30 s all-out cycling alternating with 30 s rest	Validated fatigue protocol (repeated sprints, e.g., (Collins et al., 2018))	Cambridge Gambling Task performed at rest and after a set of the 8 sprints. Response: micro-movement	Less deliberation time, increased risk-taking on ascending trials, but no change in risk adjustment
Parkin et al. (2017)	23 athletes (11 female) Age: 28.25 y (range = 23-36 y) Experience: world-class elite; training for about 20 y; international championship experience; classified as world-class and successful-elite based on Swann et al. (2015)	8 repetitions of 30 s all-out cycling alternating with 30 s rest	Validated fatigue protocol (repeated sprints, e.g., (Collins et al., 2018))	Computerized Stroop test with four colours performed at rest and after a set of the 8 sprints. Response: micro-movement	No differences in response time for congruent or incongruent trials
Thomson et al. (2009)	163 male ball sport athletes (soccer [79], basketball [63], volleyball [21])	Incremental treadmill test to volitional exhaustion	Volitional exhaustion	Computerized speed discrimination task of square shapes	Decrease in response time and increase in number of errors

	Age: 21.17 ± 4.18 y Experience: Estonian National League			moving at different virtual velocities performed before and after the incremental protocol. Response: micro-movement		
Zarrouk et al. (2016)	8 male karate athletes Age: 17.2 ± 0.5 y Experience: training at least 2h/day, 5 days/wk for at least 3 y; Tunisian regional team	Sub-maximal isometric elbow flexion at 75% MVC until volitional exhaustion	Volitional exhaustion	Four-choice reaction time test before and after the fatiguing protocol. Response: micro-movement	No change in reaction time	
Fatigue from mental exertion						
Sport-specific						
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Non-specific						
Alder et al. (2021)	16 male soccer players Age: 22.4 ± 2.5 y Experience: 14 ± 3.6 y; semi-pro UK teams	30-min verbal Stroop test	Validated fatigue protocol (e.g., (Gantois et al., 2020))	Video-based anticipation test with 3 response options performed before and after the fatigue protocol. Response: verbal	Decrease in accuracy compared to baseline measures and the physical load-only and mental-load only conditions	Higher RSME than for the physical load
Badin et al. (2016)	20 soccer players Age: 17.8 ± 1 y Experience: 8.3 ± 1.4 y; Australian National Premier league	30-min computerized Stroop test with four colours and a including a switch stimulus Control: 30-min documentary	Higher subjective rating of mental fatigue after the Stroop compared to the control condition	Small-sided game (2 x 7 min with 1-min halftime) performance after the fatigue protocol and compared to the control condition.	Decrease in ratio of positive to negative involvements and possessions. Decrease in tackle success. Decrease in pass accuracy.	Trivial or higher postgame ratings of mental fatigue. Higher postgame ratings of mental effort

				Response: sport performance	
D. Coutinho et al. (2018)	10 soccer players Age: 13.7 ± 0.5 y Experience: 6.1 ± 0.9 y; regional soccer academy	30-min computerized Stroop test with four colours and including a switch stimulus Control: no treatment	Increase in subjective rating of mental fatigue	Small-sided games (3 x 6 min) performed after the fatigue protocol and compared to the control condition. Response: sport performance	Decrease in APEn, decrease in team stretch index, decrease in time spent synchronized in longitudinal displacements
Fortes et al. (2019)	20 male soccer players Age: 24.7 ± 3.6 y Experience: 10.2 ± 2.1 y; professional (Third Division of Brazilian Soccer League)	30 or 45 min of social media use Control: 30 min of a coaching video	Worse accuracy and response time on a Stroop test compared to the control condition	Simulated match of two 45-min halves with a 15-min halftime after the fatigue protocol and compared to the control condition. Response: sport performance	Lower passing decision-making performance
(Fortes et al., 2020)	25 soccer players Age: 23.4 ± 2.8 y Experience: 8.7 ± 3.3 y; professional (Brazilian Soccer Confederation)	30 min of social media use Control: 30 min of advertisement videos	Worse accuracy and response time on a Stroop test compared to the control condition	Simulated match of two 45-min halves with a 15-min halftime after the fatigue protocol and compared to the control condition. Response: sport performance	Lower decision-making scores
Fortes et al. (2020)	25 soccer players Age: 23.4 ± 2.8 y Experience: 8.7 ± 3.3 y; professional (Brazilian Soccer Confederation)	30 min of video games Control: 30 min of advertisement videos	Worse accuracy and response time on a Stroop test compared to the control condition	Simulated match of two 45-min halves with a 15-min halftime after the fatigue protocol and compared to the control condition.	Lower decision-making scores

				Response: sport performance		
Fortes, Gantois, et al. (2021)	21 boxers (8 female) Age: 23.33 ± 3.4 y Experience: 8.9 y; amateur (7 national level, 13 regional level)	30 min of social media use Control: 30 min of a coaching video	Worse response time on a Stroop test and a higher subjective rating of mental fatigue compared to the control condition	Simulated combats of four 2-min rounds with 1-min rest after the fatigue protocol and compared to the control condition. Response: sport performance	Lower attack and defence decision-making performance	Higher RPE after the simulated combats compared to the control condition
Fortes, Gantois, et al. (2021)	21 boxers (8 female) Age: 23.33 ± 3.4 y Experience: 8.9 y; amateur (7 national level, 13 regional level)	30 min of video games Control: 30 min of a coaching video	Worse response time on a Stroop test and a higher subjective rating of mental fatigue compared to the control condition	Simulated combats of four 2-min rounds with 1-min rest after the fatigue protocol and compared to the control condition. Response: sport performance	Lower attack and defence decision-making performance	Higher RPE after the simulated combats compared to the control condition
Gantois et al. (2020)	20 soccer players Age: 22.6 ± 3.3 y Experience: professional	30-min computerized Stroop test with four colours Control: 30 min of advertising videos	Worse response time on a Stroop test compared to the control condition	Simulated match of two 45-min halves with a 15-min halftime after the fatigue protocol and compared to the control condition. Response: sport performance	Lower passing decision-making performance	No difference in sRPE between the conditions
Kosack et al. (2020)	19 male badminton players Age: 20 ± 2.8 y Experience: 12.5 ± 3.5 y; national elite	60-min computerized Stroop with four colours and including a switch stimulus Control: 60-min documentary	Higher subjective rating of mental fatigue after the Stroop compared to the control condition	Badminton-specific test (BST) performed after the fatigue protocol and compared to the control condition: Four sensors in each of	No difference in test completion time	No difference in RPE for the BST between the conditions. Similar MF after the BST between conditions

				the badminton court corners athletes had to hit with a racket based on a visual signal shown on computer in the middle front court. Response: whole-body movement		
Kunrath, Nakamura, et al. (2020)	18 male soccer players Age: 21.8 ± 2.5 y Experience: varsity first team and national and state league competition	30-min computerized Stroop with four colours and including a switch stimulus Control: 30-min documentary	Increase in subjective rating of mental fatigue	Peripheral perception task before and after the Stroop test. Response: micro-movement	Decrease in visual field	
Kunrath, Nakamura, et al. (2020)	18 male soccer players Age: 21.8 ± 2.5 y Experience: varsity first team and national and state league competition	30-min computerized Stroop with four colours and including a switch stimulus Control: 30-min documentary	Increase in subjective rating of mental fatigue	Small-sided game (12 min) performed after the fatigue protocol and compared to the control condition. Response: sport performance	Lower accuracy on FUT-SAT measures of offensive coverage, width and length, offensive unity, delay, balance, concentration, defensive unity	
M. R. Smith et al. (2016)	12 male soccer players Age: 19.3 ± 1.5 y Experience: 13.1 ± 2.6 y; Belgian national or provincial competitors	30-min paper Stroop with four colours and including a switch stimulus Control: 30 min of reading magazines	Increase in subjective rating of mental fatigue and higher rating after Stroop compared to after the control condition	Video-based decision-making test performed after the fatiguing protocol and compared to the control condition. Response: verbal and whole-body movement	Overall, lower response accuracy and slower response time	Trivial or higher mental effort after the decision-making test. Trivial or higher motivation to perform the decision-making test. Similar mental fatigue after the decision-making test between conditions

Trecroci et al. (2020)	9 soccer players Age: 17.6 ± 0.5 y Experience: sub-elite (semi-pro academy U19 team)	30-min Stroop using smartphone app Control: 30 min documentary	Increase in subjective rating of mental fatigue	Small-sided game (2x 7 min with 1-min halftime) after the fatigue protocol and compared to the control condition. Response: sport performance	Lower passing and dribbling decision-making performance. Lower passing and shot accuracy	Higher RPE after the SSG than the control condition. Higher mental fatigue after the SSG. Higher mental effort after the SSG. No differences in motivation compared to control group before the SSG
Van Cutsem et al. (2019)	9 badminton players (4 female) Age: 23 ± 3 y Experience: ≥ 8 y; national or international competitors	90-min computerized Stroop protocol with four colours and including a switch stimulus Control: 90-min documentary	Decrease over time of Stroop performance on switch stimuli; higher subjective rating of mental fatigue and of task load after the Stroop compared to the control condition	Visuomotor test with Fitlights performed before and after the treatment, requiring participants to put out the light (simple stimuli) or turn around and put out a light behind them (complex stimuli). Response: whole-body movement	No change in accuracy. Slower response time post-fatigue for complex stimuli compared to pre-fatigue	
Van Cutsem et al. (2019)	9 badminton players (4 female) Age: 23 ± 3 y Experience: ≥ 8 y; national or international competitors	90-min computerized Stroop protocol with four colours and including a switch stimulus Control: 90-min documentary	Decrease over time of Stroop performance on switch stimuli; higher subjective rating of mental fatigue and of task load after the Stroop compared to the control condition	Incongruent Flanker test performed before and after the treatment. Response: micro-movement	No change in accuracy or response time	
Weerakkody et al. (2021)	25 male Australian Football players Age: 23.8 ± 4.6 y Experience:	30-min computerized Stroop test	Decrease in Stroop test performance	Modified Matthew Lloyd clean hands test performed after the fatiguing	No change in execution quality	

	community-level, competing in metropolitan or reional leagues in mid/low-level divisions	Control: 30-min documentary		protocol (and after a number of physical assessments) and compared to the control condition (in the same order relative to the physical assessments). Response: whole-body performance		
Fatigue from combined physical and mental exertion						
Sport-specific						
Bradley et al. (2014)	103 soccer players (59 female) Age: unspecified Experience: elite; UEFA Champions League	Full-length competitive match	Full-length match	Match technical performance compared between the two halves. Response: sport performance	Decrease in number of total balls lost in second half (males only)	
Carling and Dupont (2011)	11 soccer players Age: unspecified Experience: professional (first French league)	Full-length competitive match	Full-length match	Match performance, analyzed in the first 5 min (0-5 min), last 5 min (85-90 min), as a mean of all other periods (5-85 min), and for each 15-min interval throughout the game. Response: sport performance	No differences in passing accuracy, possessions gained/lost, percentage of duels won/lost	
Michailidis et al. (2018)	Specific participants unspecified (match analysis) Experience: professional (UEFA	Full-length competitive match	Full-length match	Match performance for each 15-min interval throughout the game.	More goals scored in the second half. Lower shot accuracy during	

	Champions League)			Response: sport performance	stoppage time and extra time
Murphy et al. (2013)	12 male Rugby League players Age: 19.9 ± 1.7 y Experience: ≥ 5 y at regional or amateur competitive level; amateur	Full-length competitive match	Full-length match	Computerized Stroop task performed before and after the match. Response: micro-movement	Uninterpretable
Nedelec and Dupont (2019)	16 soccer players Age: 18.5 ± 2.5 y (goalkeepers); 17.1 ± 1.0 y (outfield players) Experience: professional or amateur high-level	Full-length competitive match	Full-length match	Vienna Determination Test: choice reaction time test with responses using hands or feet performed one week before and 45 min after the match. Response: micro-movement	Greater number of stimuli and correct responses
Rampinini et al. (2009)	186 male soccer players Age: 27 ± 4 y Experience: professional (top Italian league: Serie A)	Full-length competitive match	Full-length match	Match technical performance compared between the two halves. Response: sport performance	No difference in percentage of successful short passes
Sepahvand et al. (2017)	10 female futsal players Age: 20 ± 2 y Experience: unspecified	Full-length match	Full-length match	Paced auditory serial test performed before and after the match, requiring participants to verbalize the sum of the previous two numbers presented in the series. Response: verbal	Increase in number of correct responses, faster response speed, longer longest series of correct answers, shorter longest series of wrong answers

Skein et al. (2013)	11 male Rugby League players Age: 20.4 ± 2.5 y Experience: varsity	Full-length competitive match	Full-length match	Computerized Stroop test performed before and after the match. Response: micro-movement	Uninterpretable	
(Wilson et al., 2020)	20 male soccer players Age: 19.5 ± 1.5 y Experience: 12.3 ± 2.4 y; top tier British varsity and 13/20 with pro academy experience	Small-sided games (6 x 2-min with 1-min breaks)	Decrease in individual performance in one or more of: countermovement jump height, 5 m acceleration, 20 m sprint, change-of-direction performance	Soccer-specific anticipation test performed before the 1st and after the 3rd, 5th, and 6th games, in which participants races a tester in a direction based on the movement initiated by the tester. Response: whole-body movement	A tendency to initiate movement earlier in response to the tester's change of direction	
• Non-specific						
Alder et al. (2021)	16 male soccer players Age: 22.4 ± 2.5 y Experience: 14 ± 3.6 y; semi-pro UK teams	Drust running protocol (40 min of 15 blocks of jogging, sprinting, walking) with 25 Stroop trials after each quarter	Validated fatigue protocols ((Drust et al., 2000; Gantois et al., 2020)	Video-based anticipation test with 3 response options performed before and after the fatigue protocol. Response: verbal	Decrease in accuracy compared to baseline measures	Higher RSME than the physical and mental load conditions. Similar RPE to the physical load condition

RMSE = rating scale of mental effort; RPE = rating of perceived exertion; sRPE = session rating of perceived exertion

4.6 Supplementary material: Appendix B

Table 4.3. Summary of main relevant conclusions of reviews, chapters, and other articles.

Reference	Publication type	Purpose	Type of exertion causing fatigue	Relevant conclusion(s)
Aitken and MacMahon (2019)	Focused review	Provide an understanding of the effects of cognitive fatigue on physical performance with an emphasis on different types of physical tasks requiring different cognitive loads	Mental	The degree to which cognitive fatigue affects physical performance depends on the cognitive demands of the physical task. Consistent with the limited-resource model of self-control, existing literature shows cognitively demanding tasks may deplete cognitive resources and impair subsequent physical performance on tasks that depend on similar resources. The amount of executive control/cognition required, not the duration, of the target task is a significant factor. Expertise, motivation, and willpower belief may mediate/moderate cognitive fatigue effects.
Brown et al. (2020)	Systematic review and meta-analysis	Integrate the findings from mental fatigue and self-control/ego-depletion literature as they relate to physical performance to carry out a comprehensive review of research examining the effects of prior cognitive exertion on physical performance in healthy individuals	Mental	Cognitive exertion is associated with greater mental demand, perceptions of fatigue, reduced task self-efficacy, affective valence, and intended physical exertion. Tasks requiring precision or sustained regulation of effort are most sensitive to negative effects induced by prior cognitive exertion. Cognitive effort may be more important than the duration of the task with regards to eliciting negative carryover effects. There has been little theorizing about why motor performance is negatively affected following cognitive exertion; it is plausible that regulation of attentional effort plays an important role in the planning and successful execution of motor tasks.
Clemente et al. (2021)	Systematic review	Compare the effects of mental fatigue vs. control conditions in terms of the total running	Mental	A mental fatigue-inducing protocol applied before performing SSGs has no significant effects on tactical behaviors compared to control conditions. Although some studies showed otherwise, these findings should

		distance and tactical behavior of soccer players during SSGs		be interpreted with caution since no consensus has been reported in the literature.
Englert et al. (2021)	Chapter	Discuss empirical findings that highlight the importance of self-control for sports-related performance, introduce the theoretical accounts that try to explain why self-control sometimes appears to fail, discuss open research questions to improve our understanding of how self-control operates and why it cannot be applied at all times and at all costs	Mental	Prior mental exertion specifically impacts types of physical performances in which self-control is critically present. When an athlete is mentally fatigued, their decision making (as well as endurance performance and movement precision) are likely to suffer. There is an important link between self-control and mental fatigue.
Habay et al. (2021)	Systematic review	Examine the effect of mental fatigue on sport-specific psychomotor performance and create an overview of the potential subjective and physiological factors underlying this mental fatigue effect	Mental	Mental fatigue impairs sport-specific psychomotor performance, but this impairment is not apparent in every measured sport-specific psychomotor performance outcome. The effect of mental fatigue on accuracy and reaction time is linked to incorrect or delayed interpretation of visual stimuli, unadjusted movement responses, or delayed movement executions.
Hornery et al. (2007)	Review	Quantify the effects of fatigue on tennis performance	Physical and combined	There are anecdotal claims of reduced performance capacity during matches of prolonged duration or those contested under hot, humid conditions. Functional tennis skills are impaired only under extreme forms of physiological stress (i.e., exhaustive cardiovascular strain, hyperthermia, dehydration). Under physiological strain, stroke accuracy is largely maintained whereas stroke velocity is more likely to deteriorate. As the state of physiological fatigue becomes imminent, players may alter their stroke intention, electing to avoid errors, rather than attempting to hit winners.
Jukic et al. (2011)	Conference proceeding	Review current scientific literature engaged in investigating the effect of fatigue on coordination and skill-related performance in team sports	Combined	Decrements in technical performance after fatigue have been documented in several studies conducted with different fatiguing protocols. Physical,

				psychological, and biomechanical factors are responsible for decrements in performance proficiency.
Knicker et al. (2011)	Review	Take a holistic and interdisciplinary approach to i) describe in general terms how fatigue is assessed at the muscle, exercise, or competition performance levels; ii) describe specifically how fatigue is manifested during sport events; iii) consider whether neuromuscular, motor skill and subjective symptoms of fatigue are linked through common mechanisms/processes	Physical and combined	In team-game sports, symptoms/measures of fatigue include increased RPE, unchanged mental concentration, and improved decision making. In racquet sports, anecdotal symptoms/measures include increased error rate, and increases in mental lapses, while measured symptoms include increased RPE. To date, there is no evidence supporting impaired decision making in sport events.
Kunrath, Cardoso, et al. (2020)	Systematic review	Verify mental fatigue effects on physical, technical, tactical, and cognitive performance in soccer players	Mental	Mental fatigue negatively influences tactical and cognitive performance of soccer players. Tactical synchronization variables (e.g., longitudinal synchronization, team contraction velocity) do not represent performance indicators, since the result of tactical actions was not considered; they are collective tactical behavior.
Pageaux and Lepers (2018)	Narrative review	Review the results of literature published between 2009-2018 that focuses on the impact of mental fatigue on sport-related performance	Mental	Mental fatigue impairs the execution of sport-related specific technical skills and negatively affects athletes' decision making during sporting events.
Reid and Duffield (2014)	Review	Discuss available literature in terms of the physiological, mechanical, and psychological responses that occur during prolonged tennis match play in the context of their likely effect on match-play performance	Combined	The effect of fatigue on stroke outcomes is ambiguous. Whether stroke outcomes are altered in accordance with increased RPE at the end of match-play is speculative. It is plausible but has not been established in prolonged match-play situations, that increased RPE (mental or physical) may alter technical and tactical engagement. Reduction in motivation to perform may be viewed as part of the fatigue process, irrespective of the capacity of the muscle to contract. Exertion and motivation may be affected by the physical state, which may lead to alterations in stroke play and/or movement patterns, but these studies occur in fabricated environments, where the motivation to perform is

				distinct from real competitive scenarios. Emerging evidence would appear to point to players altering their tactical and, therefore, technical strategies to accommodate deterioration in physiological function.
Russell, Jenkins, Smith, et al. (2019)	Review	Review the literature relevant to mental fatigue and team sporting performance to provide perspectives on the transferability and significance of the evidence to the applied elite sporting context	Mental	Mental fatigue has the potential to negatively impact decision-making accuracy, increase response time, and impair the ability to effectively use environmental information in a time-appropriate way.
Russell, Jenkins, Rynne, et al. (2019)	Original investigation	Investigate the perceptions of athletes and staff across a variety of elite sport contexts regarding their understandings of MF	Mental	In addition to mental fatigue causing tasks to feel harder, quality of movement and intensity may be compromised. Furthermore, mental fatigue may be associated with difficulty concentrating, decreased awareness, and decreased ability to make correct decisions in competition and training. Mental fatigue-associated decreased impulse control and difficulty concentrating may also be linked with incorrect decisions.
Russell, Kelly, et al. (2020)	Chapter	Discuss specifics of cognitive load through a human factors perspective and provide practical recommendations for the assessment and management of cognitive load	Mental	Cognitive demands required during sport may increase one's mental fatigue and reduce the subsequent capacity to self-regulate. Cognitive fatigue may impair physical, technical, tactical, and psychological components of sporting performance.
Russell and Kingsley (2011a).	Review	Summarize current research that evaluates technical responses to exercise, using soccer as the main area of interest	Combined	While it is difficult to evaluate the skilled response to exercise, and exercise-induced effects of fatigue vary according to the soccer skill, it appears there is a fatigue-associated decline in technical performance. Shooting performance may be the most susceptible to exercise-induced fatigue. Skill tests that produce criterion-based outcome measures circumvent some challenges associated with assessing skills during match-play, but makes for results that are hard to interpret due to the low ecological validity.

Schmit and Brisswalter (2020)	Review/perspective	Address strengths and weaknesses of empirical studies in exercise-cognition to initiate a neurocognitive reasoning of exercise-related executive impairment	Physical	Prolonged exercise leads to self-regulatory failure, which results in decreased cognitive performance. Authors propose a dynamical model to explain how exercise-related fatigue manifests as executive functioning becoming less effective than at rest: initially, exercise-related arousal upregulates prefrontal cortex activity, improving executive functioning and self-regulatory performance. As duration increases, physical demand increases, competing for the limited capacity of information processing of the prefrontal cortex and increasingly hindering executive functioning. "Fatigue" occurs when self-regulatory performance returns to baseline or worse.
Sun et al. (2021)	Systematic review	Report a comprehensive systematic review investigating the carryover effects of mental fatigue on skilled performance among athletes	Mental	There are, in general, negative effects of mental fatigue on skilled performance in sports, but the effects vary depending on the task's demand. No physiological or psychological indicator mediated effects of mental fatigue on skilled performance.
Thompson et al. (2019)	Current opinion	Critically examine the methodological approach to investigating mental fatigue on task performance, most notably the lack of ecological validity when inducing mental fatigue and the visual analog scale approach to measure it	Mental	Induced mental fatigue negatively influences physical, skill, decision-making, technical, and tactical aspects of football performance, in isolated performance tests and small-sided games. However, these studies are limited by tasks with low ecological validity to induce fatigue and the use of a subjective tool (visual analog scale) to measure mental fatigue.
Van Cutsem and Marcora (2021)	Chapter	Discuss experimental studies investigating the effects of acute mental fatigue induced by prolonged and demanding cognitive tasks on physical and psychomotor components of sport performance	Mental	In general, there is a negative impact of mental fatigue on psychomotor performance. Studies where this effect was not observed could be because of motivation, talent, test validity, or a large anaerobic component to the target task. There are interactions between task duration, difficulty and engagement that should be considered for the inducement of mental fatigue, (i.e., not just duration).

RPE = rating of perceived effort

4.7 Online supplementary material

4.7.1 Inclusion criteria

4.7.1.1 Primary literature full text inclusion criteria, hierarchically organized

1. Healthy, non-injured athletes, or participants with reported previous specific sports experience. Include if there are injured athletes, as long as there is a control group. Exclude Armed Forces personnel, “trained participants”, “active participants”, “resistance-trained participants”, but include “trained athletes”.
2. There is a cognitive outcome of interest. This includes any parameters related to pacing, perception (affect, pain, etc.), neuromuscular activation (EMG), traditional neuropsychological tests, coordination (kinematics, postural control), and sport-specific tasks or games. This not an exhaustive list.
3. Outcome of interest is measured at two or more time points or on two or more occasions, or among two or more groups (i.e., control vs. fatigued) with the independent variable being acute exertion/fatigue (single-session, not chronic, and not related to sleep deprivation). For now, don’t worry about the presence of a manipulation check.
4. Outcome of interest is NOT effort-based decision-making related to endurance performance (e.g., time trial performance, time to fatigue). Stroke rate, cadence, and stride length will be considered as effort-based decision-making.
5. Outcome of interest is performance on a perceptual-cognitive/psychomotor/perceptual-motor task that is evaluated or judged (e.g., objective passing accuracy, objective right/wrong Stroop response, subjective decision quality rating) and not just quantified (e.g., number of tackles). Continue down the list even if there is no temporal or spatial uncertainty, e.g., self-paced basketball free throws, Loughborough Soccer Passing Test, etc.
6. A manipulation check confirms that fatigue was induced.
7. Open-skilled sport athletes, or participants with reported previous open-skilled sport experience.
8. Performance task is perceptual-cognitive, according to our full definition: it involves spatial (“where” to move/ “what” response to execute) and/or temporal (“when” to move/respond) uncertainty. Additionally, the exact movement is not preplanned.
9. If ergogenic aids, nutritional supplementation, hydration and/or environmental manipulations are present, there IS a control or placebo group.

4.7.1.2 Secondary literature full text inclusion criteria, hierarchically organized

1. Mentions “fatigue” or “exhaustion” explicitly as a variable of interest (i.e., not just acute exercise).
2. Presents or discusses the effects or consequences of fatigue/exhaustion on a cognitive outcome of interest. “Cognitive outcomes of interest” encompass in-game sport performance, performance on sport-specific tasks, perceptual responses, effort-based decision making, and performance on traditional cognitive tests. Brain or neuromuscular activation will not be considered.
3. Explicitly contextualizes the effects of fatigue on the cognitive outcome of interest within sport or discusses the relevance to sport performance (i.e., does not exclusively examine general exercise performance). For example, if the cognitive outcome of interest is effort-based decision making related to endurance exercise performance, it must be reasonably linked to an athlete population or competitive performance.
4. There is at least one outcome of interest that is NOT effort-based decision making related to endurance performance (e.g., time trial performance, time to fatigue). Only select “no” if they are.
5. Outcome of interest is performance on a perceptual-cognitive/psychomotor/perceptual-motor task that is evaluated or judged (e.g., objective passing accuracy, subjective decision quality) and not just quantified (e.g., number of tackles). Consider the full definition for perceptual-cognitive, which encompasses spatial and/or temporal uncertainty. If there are multiple outcomes of interest, at least one satisfies this criterion.
6. If there are multiple outcomes of interest, the effects of fatigue on the performance of a perceptual-cognitive/psychomotor/perceptual-motor task are presented or discussed separately from the effects of fatigue on other outcomes of interest.
7. At least one of the populations of interest is, or there is good reason to suspect is, open-skill sport athletes.

4.7.2 Database search strategies

MEDLINE

MON

EBSCOhost

Friday, April 23, 2021 9:12:15 AM

#	Question	Opérateurs de restriction/Opérateurs d'expansion	Dernière exécution par	Résultats
S10	S7 AND S8 AND S9	Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Trouver tous mes termes de recherche	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - MEDLINE with Full Text	1,889
S9	AB (S5 OR S6) OR TI (S5 OR S6)	Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Trouver tous mes termes de recherche	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - MEDLINE with Full Text	288,997
S8	AB (S3 OR S4) OR TI (S3 OR S4)	Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Trouver tous mes termes de recherche	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - MEDLINE with Full Text	1,328,291
S7	AB (S1 OR S2) OR TI (S1 OR S2)	Opérateurs d'expansion - Appliquer des sujets	Interface - EBSCOhost Research Databases	232,066
S6	(MH "Athletes+") OR (MH "Sports+")	Opérateurs de restriction - Revues académiques (relues par un comité de lecture) Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Booléen/Phrase	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - MEDLINE with Full Text	184,225
S5	athlet* OR player* OR sport*	Opérateurs de restriction - Revues académiques (relues par un comité de lecture) Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Booléen/Phrase	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - MEDLINE with Full Text	274,513
S4	(MH "Judgment") OR (MH	Opérateurs de restriction -	Interface - EBSCOhost Research	267,796

	"Decision Making") OR (MH "Cognition") OR (MH "Anticipation, Psychological") OR (MH "Executive Function") OR (MH "Psychomotor Performance")	Revues académiques (relues par un comité de lecture) Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Booléen/Phrase	Databases Ecran de recherche - Recherche avancée Base de données - MEDLINE with Full Text	
S3	Decision* OR cogniti* OR executive function* OR anticipation OR attention* OR judg#ment OR psychomotor OR psycho motor OR perceptual cognitive OR perceptual motor	Opérateurs de restriction - Revues académiques (relues par un comité de lecture) Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Booléen/Phrase	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - MEDLINE with Full Text	1,471,217
S2	(MH "Muscle Fatigue") OR (MH "Physical Exertion") OR (MH "Fatigue") OR (MH "Mental Fatigue") OR (MH "Exercise Tolerance")	Opérateurs de restriction - Revues académiques (relues par un comité de lecture) Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Booléen/Phrase	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - MEDLINE with Full Text	102,295
S1	Fatigu* OR ego depletion OR exerti* OR exhausti*	Opérateurs de restriction - Revues académiques (relues par un comité de lecture) Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Booléen/Phrase	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - MEDLINE with Full Text	226,494

SPORTDiscus

MON
EBSCOhost

Friday, April 23, 2021 8:58:17 AM

#	Question	Opérateurs de restriction/Opérateurs d'expansion	Dernière exécution par	Résultats
S10	S7 AND S8 AND S9	Opérateurs de restriction - Relu par un comité de lecture Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Trouver tous mes termes de recherche	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - SPORTDiscus	667
S9	TI (S5 OR S6) OR AB (S5 OR S6) OR KW (S5 OR S6)	Opérateurs de restriction - Relu par un comité de lecture Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Trouver tous mes termes de recherche	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - SPORTDiscus	184,778
S8	TI (S3 OR S4) OR AB (S3 OR S4) OR KW (S3 OR S4)	Opérateurs de restriction - Relu par un comité de lecture Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Trouver tous mes termes de recherche	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - SPORTDiscus	69,162
S7	TI (S1 OR S2) OR AB (S1 OR S2) OR KW (S1 OR S2)	Opérateurs de restriction - Relu par un comité de lecture Opérateurs d'expansion -	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche	27,698
S6	(((DE "SPORTS teams" OR DE "AUSTRALIAN football teams" OR DE "BASEBALL teams" OR DE "BASKETBALL teams" OR DE "COLLEGE sports teams" OR DE "CURLING teams" OR DE "EXPANSION teams" OR DE "FOOTBALL teams" OR DE "HOCKEY teams" OR DE "NATIONAL sports teams" OR DE "RECREATIONAL sports teams" OR DE "REVENUE sharing in sports" OR DE	Opérateurs de restriction - Relu par un comité de lecture Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Trouver tous mes termes de recherche	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - SPORTDiscus	29,846

	"RUGBY football teams" OR DE "SOCCER teams" OR DE "SOFTBALL teams" OR DE "TENNIS teams" OR DE "TEAM sports" OR DE "BASEBALL" OR DE "BASKETBALL" OR DE "BATTLE ball" OR DE "CRICKET (Sport)" OR DE "DODGEBALL" OR DE "GOALBALL" OR DE "HOCKEY" OR DE "KICKBALL" OR DE "LACROSSE" OR DE "NATIVE American stickball" OR DE "POLO" OR DE "PUSH ball" OR DE "QUIDDITCH (Game)" OR DE "RUGBALL" OR DE "RUGBY football" OR DE "SOCCER" OR DE "SOFTBALL" OR DE "SPEEDBALL" OR DE "STOOLBALL" OR DE "TCHOUKBALL" OR DE "TETHERBALL" OR DE "VOLLEYBALL" OR DE "WALLYBALL" OR DE "WIFFLE ball")) OR (DE "COMBAT sports" OR DE "DUELING" OR DE "HAND-to-hand fighting" OR DE "MARTIAL arts")) OR (DE "RACKET games" OR DE "BADMINTON (Game)" OR DE "BASQUE pelota (Game)" OR DE "BATTLEDORE & shuttlecock" OR DE "COURT tennis" OR DE "MINTON (Game)" OR DE "PADDLE tennis" OR DE "PICKLEBALL (Game)" OR DE "POLOCROSSE" OR DE "RACKETS (Game)" OR DE "RACQUETBALL" OR DE "SQUASH (Game)" OR DE "SQUASH tennis" OR DE "TABLE tennis" OR DE "TENNIS")			
S5	athlet* OR player* OR sport*	Opérateurs de restriction - Relu par un comité de lecture Opérateurs d'expansion - Appliquer des sujets équivalents	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - SPORTDiscus	329,098

		Modes de recherche - Booléen/Phrase		
S4	DE "DECISION making" OR DE "COGNITION" OR DE "COGNITIVE ability" OR DE "ATTENTION" OR DE "PSYCHOLOGY of movement" OR DE "PERCEPTUAL-motor processes"	Opérateurs de restriction - Relu par un comité de lecture Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Booléen/Phrase	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - SPORTDiscus	16,159
S3	Decision* OR cogniti* OR executive function* OR anticipation OR attention* OR judg#ment OR psychomotor OR psycho motor OR perceptual cognitive OR perceptual motor	Opérateurs de restriction - Relu par un comité de lecture Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Booléen/Phrase	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - SPORTDiscus	81,461
S2	DE "FATIGUE"	Opérateurs de restriction - Relu par un comité de lecture Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Booléen/Phrase	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - SPORTDiscus	7,038
S1	fatigu* OR ego depletion OR exerti* OR exhausti*	Opérateurs de restriction - Relu par un comité de lecture Opérateurs d'expansion - Appliquer des sujets équivalents Modes de recherche - Booléen/Phrase	Interface - EBSCOhost Research Databases Ecran de recherche - Recherche avancée Base de données - SPORTDiscus	28,328

PsycINFO

Set	Search Statement	Annotations	Insert	Edit	Delete
1.	exp Fatigue/				
2.	(Fatigu* or ego depletion or exerti* or exhauti*).ab. or (Fatigu* or ego depletion or exerti* or exhauti*).id. or (Fatigu* or ego depletion or exerti* or exhauti*).ti.				
3.	decision making/ or judgment/				
4.	cognitive ability/ or executive function/				
5.	attention/ or attentional capture/ or focused attention/ or selective attention/ or sustained attention/				
6.	perceptual motor processes/				
7.	(Decision* or cogniti* or executive function* or anticipation or attention* or judgement or psychomotor or psycho motor or perceptual cognitive or perceptual motor).ab. or (Decision* or cogniti* or executive function* or anticipation or attention* or judgement or psychomotor or psycho motor or perceptual cognitive or perceptual motor).id. or (Decision* or cogniti* or executive function* or anticipation or attention* or judgement or psychomotor or psycho motor or perceptual cognitive or perceptual motor).ti.				
8.	exp College Athletes/ or exp Athletes/ or exp Professional Athletes/				
9.	(Athlet* or player*).ab. or (Athlet* or player*).id. or (Athlet* or player*).ti.				
10.	1 or 2				
11.	3 or 4 or 5 or 6 or 7				
12.	8 or 9				
13.	10 and 11 and 12				

EMBASE

#	Searches	Annotations	Actions
1	(Fatigu* or ego depletion or exerti* or exhausti*).mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word, candidate term word]		
2	fatigue/ or muscle fatigue/		
3	(Decision* or cogniti* or executive function* or anticipation or attention* or judg?ment or psychomotor or psycho motor or perceptual cognitive or perceptual motor).mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word, candidate term word]		
4	decision making/		
5	cognition/ or attention/ or executive function/		
6	anticipation/		
7	psychomotor performance/		
8	(Athlet* or player* or sport*).mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word, candidate term word]		
9	elite athlete/ or ball sports athlete/ or contact athlete/ or athlete/ or combat sports athlete/ or professional athlete/ or student athlete/		
10	exp team sport/ or exp ball sport/ or exp contact sport/ or exp combat sport/ or exp racquet sport/		
11	(Fatigu* or ego depletion or exerti* or exhausti* or (fatigue or muscle fatigue)).ab. or (Fatigu* or ego depletion or exerti* or exhausti* or (fatigue or muscle fatigue)).ti. or (Fatigu* or ego depletion or exerti* or exhausti* or (fatigue or muscle fatigue)).kw.		
12	(Decision* or cogniti* or executive function* or anticipation or attention* or judg?ment or psychomotor or psycho motor or perceptual cognitive or perceptual motor or decision making or (cognition or attention or executive function) or anticipation or psychomotor performance).ab. or (Decision* or cogniti* or executive function* or anticipation or attention* or judg?ment or psychomotor or psycho motor or perceptual cognitive or perceptual motor or decision making or (cognition or attention or executive function) or anticipation or psychomotor performance).ti. or (Decision* or cogniti* or executive function* or anticipation or attention* or judg?ment or psychomotor or psycho motor or perceptual cognitive or perceptual motor or decision making or (cognition or attention or executive function) or anticipation or psychomotor performance).kw.		
13	(Athlet* or player* or sport* or (elite athlete or ball sports athlete or contact athlete or athlete or combat sports athlete or professional athlete or student athlete) or (team sport or ball sport or contact sport or combat sport or racquet sport)).ab. or (Athlet* or player* or sport* or (elite athlete or ball sports athlete or contact athlete or athlete or combat sports athlete or professional athlete or student athlete) or (team sport or ball sport or contact sport or combat sport or racquet sport)).ti. or (Athlet* or player* or sport* or (elite athlete or ball sports athlete or contact athlete or athlete or combat sports athlete or professional athlete or student athlete) or (team sport or ball sport or contact sport or combat sport or racquet sport)).kw.		
14	11 and 12 and 13		

Web of Science

Set	Results	Save History / Create Alert Open Saved History	Edit Sets	Combine Sets ◯AND ◯OR Combine	Delete Sets Select All ✕ Delete
# 4	1,086	#3 AND #2 AND #1 *Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=All years*	Edit	☐	☐
# 3	348,261	TI=(Athlet* OR player* OR sport*) OR AB=(Athlet* OR player* OR sport*) OR AK=(Athlet* OR player* OR sport*) *Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=All years*	Edit	☐	☐
# 2	2,803,728	TI=(Decision* OR cogniti* OR executive function* OR anticipation OR attention* OR judg$ment OR psychomotor OR psycho motor OR perceptual cognitive OR perceptual motor) OR AB=(Decision* OR cogniti* OR executive function* OR anticipation OR attention* OR judg$ment OR psychomotor OR psycho motor OR perceptual cognitive OR perceptual motor) OR AK=(Decision* OR cogniti* OR executive function* OR anticipation OR attention* OR judg$ment OR psychomotor OR psycho motor OR perceptual cognitive OR perceptual motor) *Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=All years*	Edit	☐	☐
# 1	351,597	TI=(Fatigu* OR ego depletion OR exerti* OR exhausti*) OR AB=(Fatigu* OR ego depletion OR exerti* OR exhausti*) OR AK=(Fatigu* OR ego depletion OR exerti* OR exhausti*) *Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=All years*	Edit	☐	☐
				◯AND ◯OR Combine	Select All ✕ Delete

ProQuest Dissertations and Theses

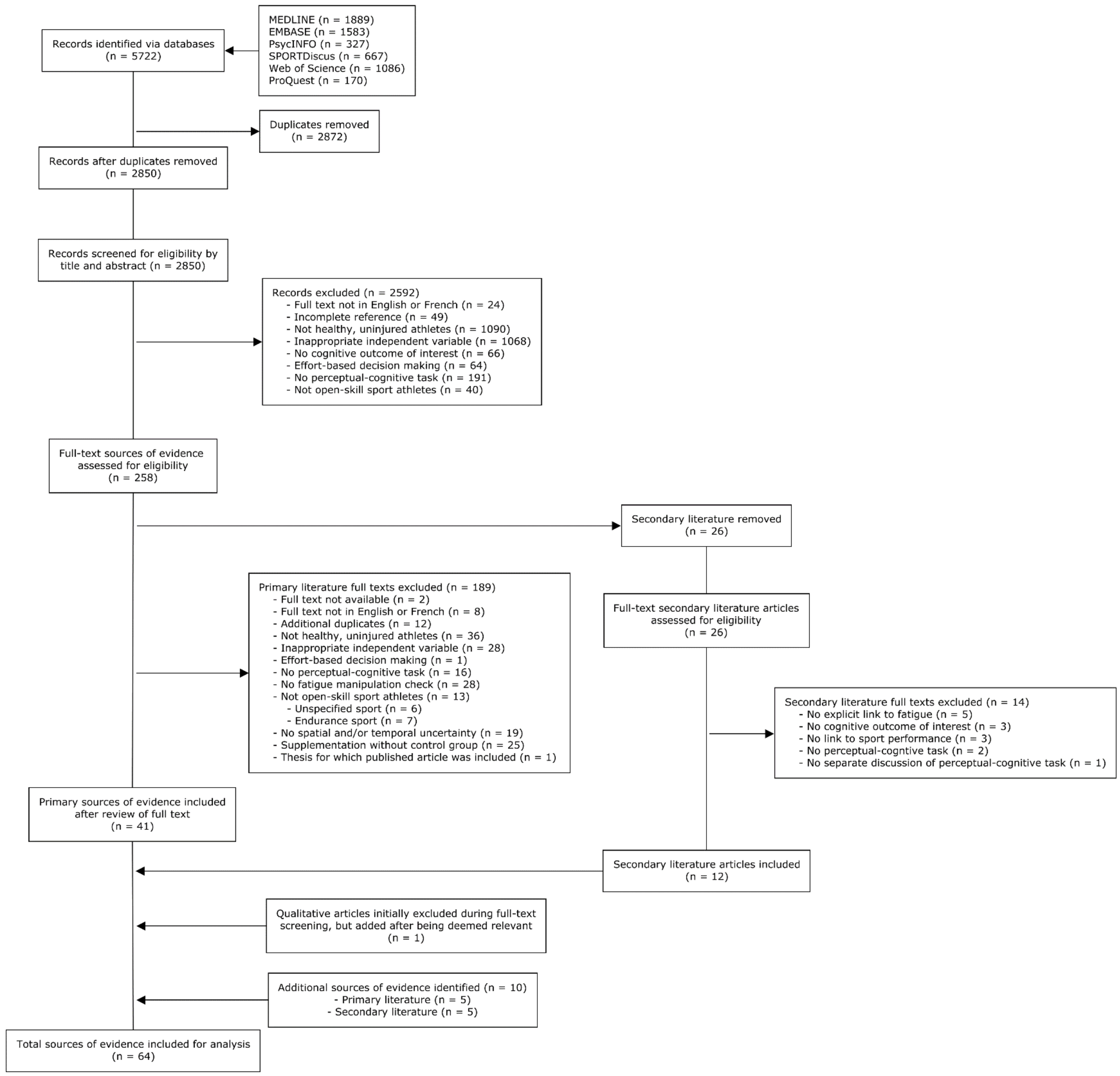
SEARCH STRATEGY

Set No.	Searched for	Databases	Results
S2	ti(Fatigu* OR ego depletion OR exerti* OR exhausti*) OR ab(Fatigu* OR ego depletion OR exerti* OR exhausti*) OR diskw(Fatigu* OR ego depletion OR exerti* OR exhausti*)	ProQuest Dissertations & Theses Global	24138
S3	ti(Decision* OR cogniti* OR executive function* OR anticipation OR attention* OR judg*ment OR psychomotor OR psycho motor OR perceptual cognitive OR perceptual motor) OR ab(Decision* OR cogniti* OR executive function* OR anticipation OR attention* OR judg*ment OR psychomotor OR psycho motor OR perceptual cognitive OR perceptual motor) OR diskw(Decision* OR cogniti* OR executive function* OR anticipation OR attention* OR judg*ment OR psychomotor OR psycho motor OR perceptual cognitive OR	ProQuest Dissertations & Theses Global	351851

	perceptual motor)		
S4	ti(Athlet* OR player* OR sport*) OR ab(Athlet* OR player* OR sport*) OR diskw(Athlet* OR player* OR sport*)	ProQuest Dissertations & Theses Global	37516
S5	(ti(Fatigu* OR ego depletion OR exerti* OR exhausti*) OR ab(Fatigu* OR ego depletion OR exerti* OR exhausti*) OR diskw(Fatigu* OR ego depletion OR exerti* OR exhausti*)) AND (ti(Decision* OR cogniti* OR executive function* OR anticipation OR attention* OR judg*ment OR psychomotor OR psycho motor OR perceptual cognitive OR perceptual motor) OR ab(Decision* OR cogniti* OR executive function* OR anticipation OR attention* OR judg*ment OR psychomotor OR psycho motor OR perceptual cognitive OR perceptual motor) OR diskw(Decision* OR cogniti* OR executive function* OR anticipation OR attention* OR judg*ment OR psychomotor OR psycho motor OR perceptual cognitive OR perceptual motor)) AND (ti(Athlet* OR player* OR sport*) OR ab(Athlet* OR player* OR sport*) OR diskw(Athlet* OR player* OR sport*))	ProQuest Dissertations & Theses Global These databases are searched for part of your query.	170
S6	(ti(Fatigu* OR ego depletion OR exerti* OR exhausti*) OR ab(Fatigu* OR ego depletion OR exerti* OR exhausti*) OR diskw(Fatigu* OR ego depletion OR exerti* OR exhausti*)) AND (ti(Decision* OR cogniti* OR executive function* OR anticipation OR attention* OR judg*ment OR psychomotor OR psycho motor OR perceptual cognitive	ProQuest Dissertations & Theses Global These databases are searched for part of your query.	170

	OR perceptual motor) OR ab(Decision* OR cogniti* OR executive function* OR anticipation OR attention* OR judg*ment OR psychomotor OR psycho motor OR perceptual cognitive OR perceptual motor) OR diskw(Decision* OR cogniti* OR executive function* OR anticipation OR attention* OR judg*ment OR psychomotor OR psycho motor OR perceptual cognitive OR perceptual motor)) AND (ti(Athlet* OR player* OR sport*) OR ab(Athlet* OR player* OR sport*) OR diskw(Athlet* OR player* OR sport*))		

4.7.3 Full flowchart depicting article screening



The scoping review helped to emphasize how methodological differences may result in different findings, as well as reinforcedthe importance of representative designs. Since our interest was primarily related to match-play fatigue and decision-making performance, it became relevant to investigate this relationship under more realistic conditions.

CHAPTER 5

THE RELATIONSHIP BETWEEN MATCH-PLAY DECISION MAKING AND FATIGUE IN ELITE WOMEN'S WATER POLO: A NOVEL RECURRENT EVENTS APPROACH

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Article under review for the *Journal of Sports Sciences*.

5.1 Abstract

Fatigue is anecdotally associated with declines in decision-making performance. This study aimed to examine if the hazard of poor decisions increased over the course of an international water polo match and a tournament. Fourteen female water polo players played six games during the 2022 FINA World Championships, reporting their fatigue before and after each match. Offensive, on-ball actions were judged as either good or poor decisions. A linear mixed model revealed that fatigue was significantly higher post-match compared to pre-match, and on the day of match 5 and 6 compared to the day of match 2 ($p < 0.05$). A total of 4491 decisions were evaluated, and piece-wise exponential additive models applied for recurrent events analyses were used to model the hazard of poor decisions. There was great variation between matches and teams in how hazard for poor decisions evolved over time. A general increase in hazard throughout match play appeared negligible in scale. Within the tournament, the cumulative hazard of poor decisions did not increase with each match. Thus, despite the development of fatigue, there was no universal increase over time in poor offensive decisions, reinforcing the relevance of also considering other factors that may influence decision-making performance.

Keywords: Elite sport, decision-making assessment, recurrent events, survival analyses, hazard

5.2 Introduction

Water polo is a high-intensity sport played in an unpredictable and dynamic environment. Accordingly, like other team sports, skillful decision making is key to successful performance (Dicks et al., 2019). Water polo matches consist of four eight-minute quarters with only two or three minutes between quarters. During international tournaments, teams play six or seven games, either on consecutive days, or more commonly, on every second day. In this context, the ability to maintain optimal decision-making performance throughout a match, as well as throughout a tournament – despite the accumulation of fatigue - can have an important impact on a team's ultimate ranking.

Researchers have demonstrated that, indeed, competitive match-play induces fatigue (Barte et al., 2017; Russell, Jenkins, et al., 2020), and that fatigue accumulates throughout a tournament (Botonis et al., 2022; Garcia et al., 2023). In water polo, playing intensity and distance covered decreases as athletes near the end of the match (Botonis et al., 2019), and male water polo athletes who played an entire match demonstrated decreases on repeated sprint ability, handgrip strength, and shooting accuracy tests performed after the match compared to before (Botonis, Toubekis, Terzis, et al., 2016). When it comes to match-play decision making, while deleterious effects of fatigue have been anecdotally described by coaches and athletes (Morgan et al., 2020; Russell, Jenkins, Rynne, et al., 2019), this has remained a complex phenomenon to quantify in many sports (Dong et al., 2022). Among junior elite male water polo players, Royal et al. (2006) found that decision making accuracy was greater after the last stage of a fatiguing test compared to after earlier stages. Although fatigue was induced using a water polo-specific drill, the video-based decision-making test involved a tactical choice indicated verbally after watching a video clip of a game scenario. While sport-specific, video-based tasks with this type of format do not create the usual perception and action demands of real gameplay. This lack of representativeness may result in an assessment of declarative game knowledge rather than match-play decision making (Dong, Berryman, et al., 2024). This makes it difficult to apply these findings to understand behaviour during competitive matches (Araujo & Davids, 2015). Additionally, despite initiatives to objectively evaluate game performance over the course of professional water polo seasons (Perazzetti, Dopsaj, Mandorino, et al., 2023), little is known about if or how decision making evolves during concentrated periods of match play, such as Olympic or World Championship tournaments.

The issue of fatigue effects on decision making has been examined among other sports, though great variation in the sport-specificity of methods used to induce fatigue and evaluate decision making makes it similarly challenging to draw conclusions (Dong et al., 2022). Consequently, how results can be extrapolated to understanding real game contexts is equivocal. Among studies that assessed in-match decision making, fatigue was induced using a domain-general cognitive task, such as social media use (Fortes, Fonseca, et al., 2021; Gantois et al., 2020), video games (Fortes et al., 2020; Fortes, Gantois, et al., 2021), or computerized cognitive tasks (Trecroci et al., 2020), while those that examined the evolution of performance over the course of matches investigated decision making more indirectly by quantifying technical-tactical outcomes, such as number of lost balls (Bradley et al., 2014), passing accuracy (Carling & Dupont, 2011), or number of goals (Michailidis et al., 2018). Notably, Kempton et al. (2013) coded technical skill performance (execution and appropriateness) throughout competitive rugby league matches to explore how it is affected by match-related fatigue. They evaluated performance in 5-min periods, making comparisons between the start and end of halves, and between peak 5-min period and other periods (Kempton et al., 2013). However, segmenting matches into 5-min periods makes it challenging to examine the evolution of performance over the entire course of a match. Thus - and perhaps surprisingly - across team ball sports, there has yet to be an investigation of if match-play decision making quality decreases as the game, and as the tournament progress.

Therefore, the objective of this study was to analyze real match-play performance and verify if, in water polo, the hazard of poor decisions increased as a match and a tournament progressed. Under the assumption that fatigue increases throughout a match and accumulates over the course of a tournament, it was hypothesized that the hazard of poor decisions would increase both withing match and a tournament.

5.3 Methods

5.3.1 Participants and context

This case study took place during the 2022 FINA World Championships in Budapest, Hungary, and focused on the Canadian Women's National Team. Normally held every two years, the World

Championships assemble the best teams across the world and represent the biggest event for the sport, other than the Olympic Games. The team, composed of fourteen elite female players (26.5 ± 2.4 years; 12 field players, including one alternate, and two goaltenders) played a total of six matches: three preliminary group stage games, one crossover game, and two classification games. Games were held on every second day, with an in-water training session on the morning of most game days and two in-water training sessions on non-game days. Players' participation consisted of filling out short questionnaires before and after each match. The study was ecological in nature with no intervention or change to the team's self-governed competition planning or routines. This study was approved by the research ethics committee at the Université du Québec à Montréal and all participants provided written consent.

5.3.2 Self-reported fatigue

Pre- and post-match questionnaires included a visual analog scale for both physical and mental fatigue, which participants rated from 0 (none at all) to 100 (maximal). Physical fatigue was defined as "a reduced capacity for maximal performance" or an "inability to complete a task that was recently achievable, solely due to physical tiredness" (Russell, Jenkins, et al., 2020), and mental fatigue was defined as "a psychobiological state caused by prolonged periods of demanding cognitive activity" (Marcora et al., 2009). Examples and/or analogies for each construct were provided.

Because integrating questionnaires at such an important event was perceived as potentially disruptive, including them at the World Championships required multiple steps. The feasibility was first tested at an international training camp before the questionnaires were administered by the first author at a lower-stakes international competition. From observation and athlete feedback, the questionnaires were subsequently moved online from their original paper format. Approximately two months before the World Championships, players were refamiliarized with the procedure by filling out the questionnaires before and after regular practices. The first author then met with athletes individually to adjust and facilitate implementation at competition. This included filling out only the post-match questionnaires (two athletes) or completing the pre-match questionnaire earlier in the day (one athlete). Otherwise, athletes answered the pre-match questions immediately before their on-land warm-up, about 20-30 minutes before entering the pool for their in-water warm up. Post-match questionnaires were completed between 15-30 minutes after the game. Athletes completed the questionnaires on an iPad mini or their personal phones. The first author was present to facilitate compliance, but respected the voluntary nature of participation.

5.3.3 Decision-making evaluation

Acknowledging that there are multiple ways of conceptualizing decision making – and that decisions are not necessarily conscious, discrete events – the current study focuses only on decision making when in possession of the ball, and attributes the label "decision" to an action that is executed: either a pass, shot, or move. A water polo-specific decision making coding instrument was adapted from Gabbett et al. (2008) and Romeas et al. (2016) through consultation with the head coach and integrated support team lead of the Canadian Women's Senior National Team, as well as the head and assistant coaches of the Canadian Men's Senior National Team (Table 1). All on-ball offensive actions were evaluated using this instrument by two experts in water polo. One was a retired Olympian from the Canadian Women's Team and the other was a coach with 15 years of coaching experience, including 9 years as head coach of a provincial team. The evaluators used the official game video footage posted on YouTube by FINA (now World Aquatics). They manually timestamped and coded every single offensive on-ball action as either a good or a bad decision. The evaluators sent their independent assessments to the first author, who identified disagreements. The three then reviewed the video of each action for which there was a disagreement, resolving it by consensus and adjusting the coding instruments when relevant (e.g., to reduce ambiguous wording or characterizations exposed during the discussion). The games were evaluated in a random order.

Table 5.1. Decision-making scoring guide.

Game action	"Good" decision – 1 point	"Poor" decision – 0 points
Pass Intentionally disposing of the ball. This includes passes to the goalie. Passes by the goalie or the pass/tip after restarting play are not evaluated.	The player made a good decision when the pass went to a teammate who was open and it: ▹ directly or indirectly created a shot attempt, or ▹ went to a teammate who was in a better position than the passer.	The player made a poor decision when the pass was: ▹ made to a player who was closely guarded or when there was a defensive player positioned in the passing line, or ▹ intercepted or turned over, or ▹ made to an area of the field where no teammate was positioned, or ▹ thrown out of the field of play, or ▹ not constructive to the play and either unproductively wasted shot clock time or was inappropriate given the time remaining on the shot clock.
Move A change in body position by the player, while in possession of the ball. This includes swimming or sliding; taking a foul, successfully or not; intentional or convincing faking; two or more fakes preceding a shot or pass. It does not include swimming to the ball to retrieve it after a bad pass.	The player made a good decision to move with possession of the ball if it created: ▹ space for teammates, or ▹ a scoring opportunity, or ▹ space for themselves, or ▹ (if faking) elicited a response from the defending team.	The player made a poor decision to move with possession of the ball if it was done: ▹ when the defenders were in good defensive position, or ▹ into a supporting defender that was in good position, and this did not create space for the dribbler or teammates, or ▹ out of the field of play, or ▹ the immediate defender was in a good position to defend the move, or ▹ without purpose and either unproductively wasted shot clock time or was inappropriate given the time remaining on the shot clock.
Shot Directing or releasing the ball at the net with the objective of scoring	The player made a good decision to shoot when: ▹ they were open for the shot and it was uncontested, or ▹ they were able to overcome contest by a defender to score, or ▹ it was the most appropriate action given the time remaining on the shot clock.	The player made a poor decision to shoot when the shot did not result in a goal and: ▹ was taken off balance, or ▹ was taken when there was good defensive coverage of the net, or ▹ was taken when it was contested by an immediate defender, or ▹ was taken when teammates were not ready to cover a counterattack, or ▹ was inappropriate given the time remaining on the shot clock, or ▹ the ball should have gone to a teammate who was in a distinctly better position to score than the shooter, or ▹ was poor shot selection.

5.3.4 Analyses

5.3.4.1 Fatigue

A linear mixed model was conducted for self-reported fatigue. Timing (pre-match, post-match), Fatigue type (mental, physical), Match number (1, 2, 3, 4, 5, 6), and their three-way interaction were included as fixed factors, while participant was included as a random factor. Effects of model fixed factors were interpreted using type III ANOVA tables and omega squared (ω^2_p) effect sizes were calculated (Lakens, 2013). Effects were considered small ($\omega^2_p = 0.01$), medium ($\omega^2_p = 0.06$), or large ($\omega^2_p = 0.14$) (Cohen, 1988). The intraclass correlation coefficient (ICC) was computed to estimate the proportion of variance due to the variable *Participant*. Significant effects were followed-up with Bonferroni-corrected post-hoc pairwise comparisons of estimated marginal means (EMM). An alpha level of 0.05 was set as the significance cut-off.

5.3.4.2 Decision making

The time-series data for decision making included the time (since the start of the game) of each offensive on-ball action, and its evaluation (good or poor decision). Differences in technical and tactical differences may be related to how unbalanced or even a game is (Lupo et al., 2014). Since playing against stronger vs weaker teams, or with a small vs large difference in score, may also influence decision making performance, variables were introduced to control for these factors. We attributed a placing differential to each game, which was the final placing (at the tournament) of the team with ball possession subtracted by the final placing of the opponent. Thus, a higher value indicates the team being evaluated is stronger. We additionally calculated a time-varying factor, goal differential, for each decision. This was the score of the team with ball possession subtracted by the score of the opponent, at the time of the decision. A higher value reflects a bigger lead for the team being evaluated. Piece-wise exponential additive models (PAMMs), applied for recurrent events analyses, were used to model the hazard of poor decisions (Bender et al., 2018; Ramjith et al., 2024).

Hazard within a match. Data from each game and team (i.e., 12 unique team-match observations, of which six were evaluations of Canada) were first transformed to piece-wise exponential data formats

(Bender et al., 2018; Ramjith et al., 2024). Calendar time was used since the interest was in the recurrent event process from the start to the end of the match, rather than in the time between events, as would be the case for gap time. To create individual-specific hazard profiles, a generalized additive model was then fitted for each of the 12 team-game combinations. New data was created based on the fitted models to estimate and visualize baseline hazard over time.

The same procedure was applied to create one model for the baseline hazard for all matches and all teams combined. After transformation to piece-wise exponential data, one generalized additive model was fitted, with placing differential and goal differential as fixed effects. The corresponding estimated baseline hazard represents the hazard if both covariates are zero. In other words, it displays the estimated hazard at a given point in time in a match if teams are evenly matched (placing differential = 0) and tied (goal differential = 0).

Hazard within a tournament. Only decision-making evaluations of Canada's games were included. For each of the six games, data were transformed into piece-wise exponential data formats, using calendar time, before a generalized additive model was fitted without covariates. Cumulative hazard was estimated by creating new data from the fitted models. For recurrent events, the cumulative hazard curve depicts the total number of events (poor decisions, in this case) accumulated up to time t, facilitating a comparison between games of the actual occurrence of events that is associated with the instantaneous hazard.

Statistical analyses were carried out using R 4.2.2 (R Core Team, 2022) and the emmeans (Lenth, 2020), lmerTest (Kuznetsova et al., 2017), and pammtools (Bender et al., 2018) packages.

5.4 Results

The self-reported responses from the alternate, who did not end up playing any games, were excluded. Two decisions, representing < 0.05% of all decisions, were excluded because no consensus could be reached.

5.4.1 Fatigue manipulation check

There were main effects of timing ($F[1, 230] = 6.11$, $p = 0.014$, $\omega^2_p = 0.02$) (Figure 5.1A) and match number ($F[5, 223] = 4.24$, $p = 0.001$, $\omega^2_p = 0.09$) (Figure 5.1B). The intraclass correlation coefficient for the model was 0.27, indicating around 27% of the variance in fatigue ratings can be attributed to individual differences. Ratings of fatigue were significantly higher post-match (estimated marginal mean ± standard error [95% CI] = 68.4 ± 3.41 [61.2, 75.6]) compared to pre-match (EMM ± SE [95% CI] = 62.6 ± 3.44 [55.3, 69.9], p = 0.015). Additionally, fatigue was higher on the days of match 5 (EMM ± SE [95% CI] = 71.7 ± 4.06 [63.4, 80.0], p = 0.0012) and 6 (EMM ± SE [95% CI] = 70.4 ± 4.06 [62.1, 78.6], p = 0.0061) compared to the day of match 2 (EMM ± SE [95% CI] = 56.3 ± 4.06 [48.0, 64.6]).

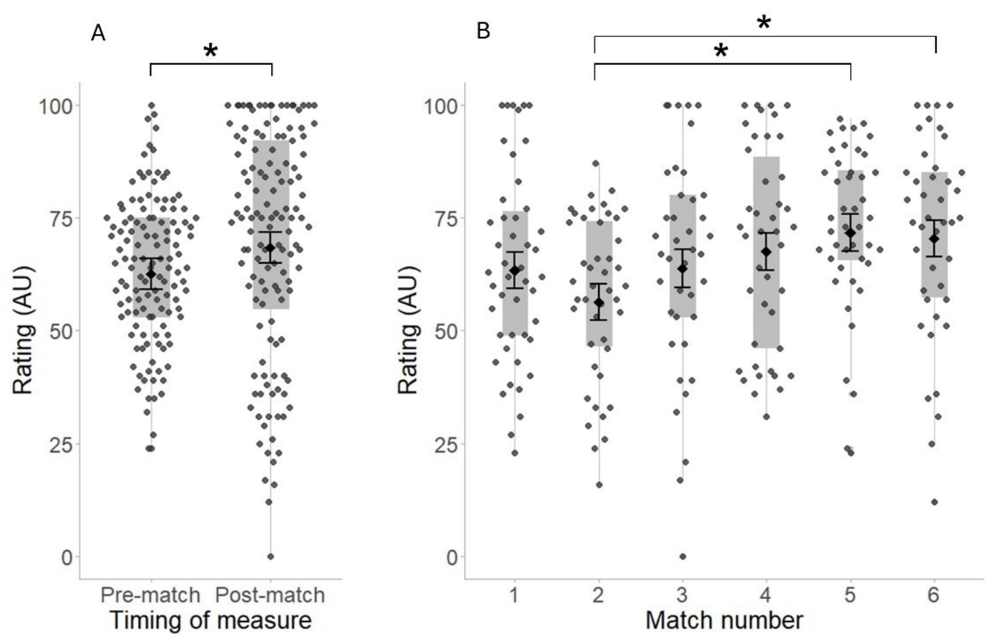

Figure 5.1. Ratings of physical and mental fatigue provided by Team Canada players. Fatigue was significantly higher post- compared to pre-match (A), as well as on the days of match 5 and 6 compared to the day of match 2 (B). There were no significant interactions or main effect of fatigue type (mental vs physical).

5.4.2 Decision making

A total of 4491 on-ball offensive actions were coded and included in the analyses. The mean number of decisions per team per match was 374.3 [range = 281-486], with means of 200.3 passes [range = 124-279], 32.6 shots [range = 23-39], and 141.4 moves [range = 112-172]. Good decisions represented a mean of 85.36% [range = 77.67-89.42%] of decisions made in a match, and Figure 2 visualizes the distribution over time of good and poor decisions (Figure 5.2). Further descriptive statistics can be found in the Supplementary Material.

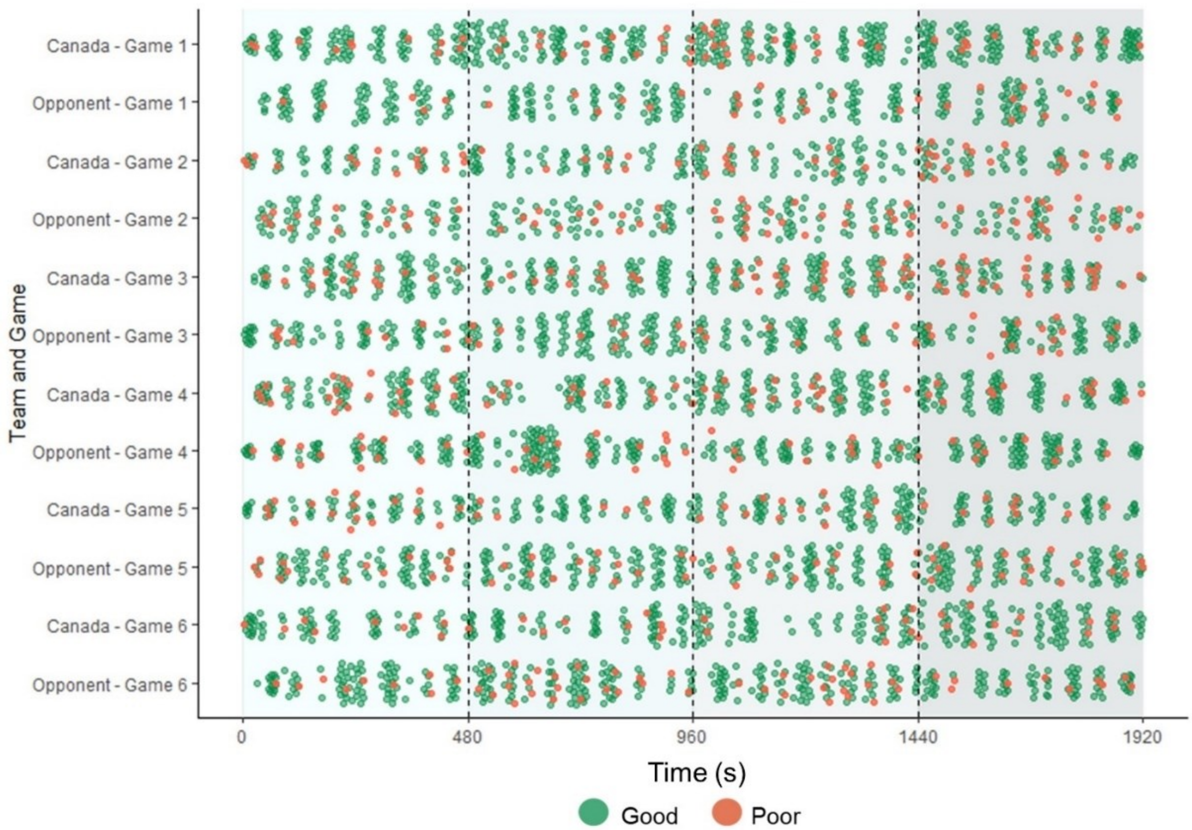

Figure 5.2. Distribution of good and poor decisions over time for the six matches in which both the Canadian and the opposing team were evaluated. The dotted lines demarcate the boundaries between match quarters.

5.4.2.1 Hazard within a game

Inspection of the baseline hazard for the models conducted for each individual game and team reveals equivocal patterns, with hazard increasing, decreasing, or remaining relatively constant depending on the match (Figure 5.3). Of note, the top row hazard functions are variable, despite all displaying the hazard for performances for the same team (Canada). Hazard appears to increase steadily from the start to the end of a match (Figure 5.4A). However, when examined at the same scale as the individual matches and teams (Figure 5.5B), the increase appears to be trivial. Neither placing differential ($p = 0.54$) nor goal differential ($p = 0.13$) had significant effects on hazard for poor decisions.

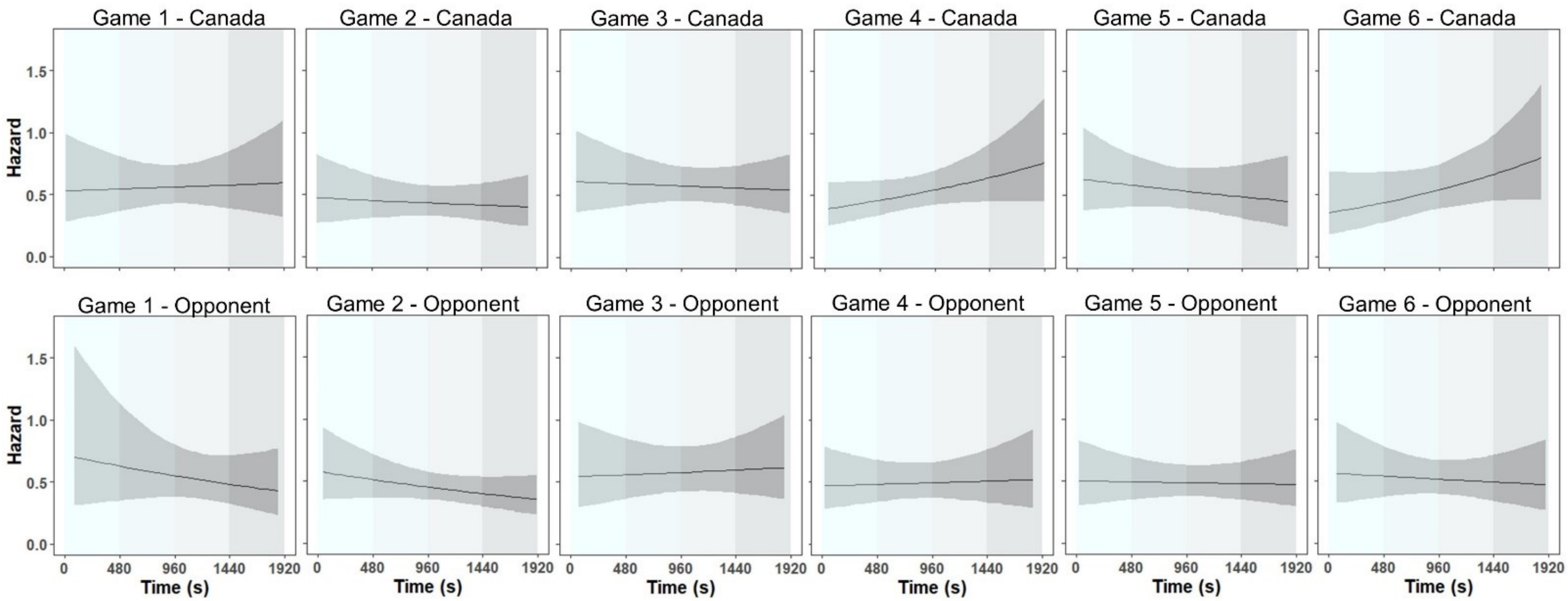

Figure 5.3. The unique profiles of the estimated baseline hazard for poor decisions for each team and game evaluated. Shaded areas represent 95% confidence intervals.

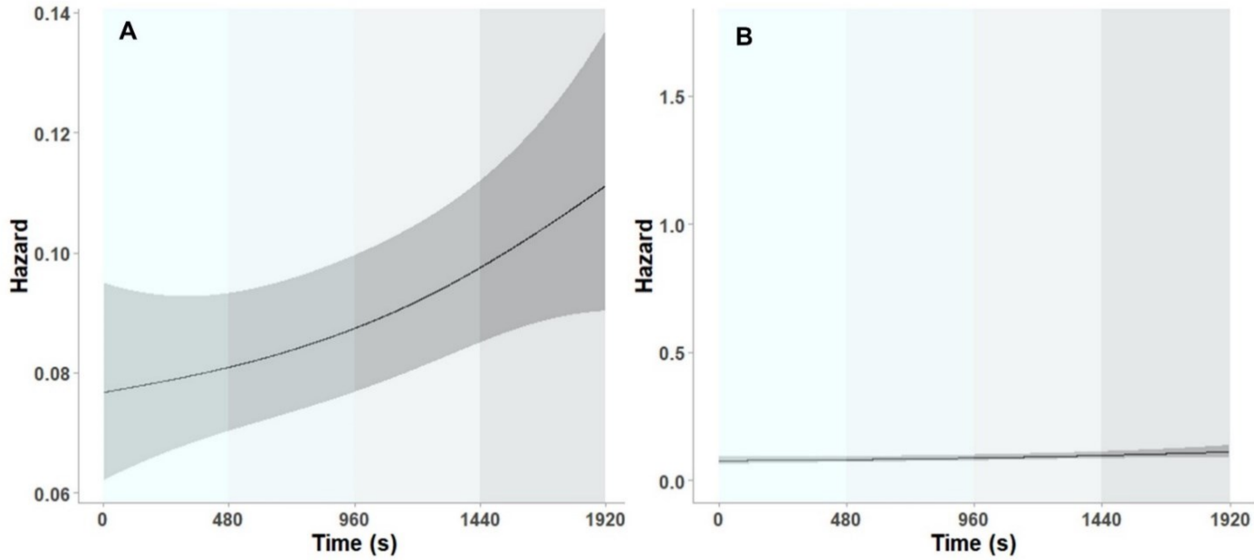

Figure 5.4. (A) Baseline hazard estimated using data from both teams for all games. (B) The same data viewed at the same scale as the individual team and game baseline hazard profiles. Data is modelled assuming goal differential and placing differential are both zero. Shaded area represents 95% confidence intervals.

5.4.2.2 Hazard within a tournament

The individual cumulative hazard curves for each of the six matches played by Canada demonstrated unique shapes. Furthermore, the cumulative hazard at the end of the match, i.e., the total number of poor decisions, was highest for match 3, followed by, in order, matches 4, 1, 2, 5, and 6 (Figure 5).

5.4.3 Discussion

Using data from real competition matches, this case study addressed the common anecdotal claim of decreased decision-making quality as fatigue develops during a match or a tournament. A total of 4491 offensive on-ball actions, performed during six World Championship water polo matches, were judged as good or poor decisions. Recurrent events analyses revealed that individual matches have unique profiles for the hazard of making a poor decision. When all teams and games were combined, there appeared to be an increase in the hazard of making a poor decision as a match unfolds, but the meaningfulness of the magnitude of the increase was questionable. Concordantly, comparisons of Canada's matches did not demonstrate that the hazard of poor decisions increased as the tournament progressed.

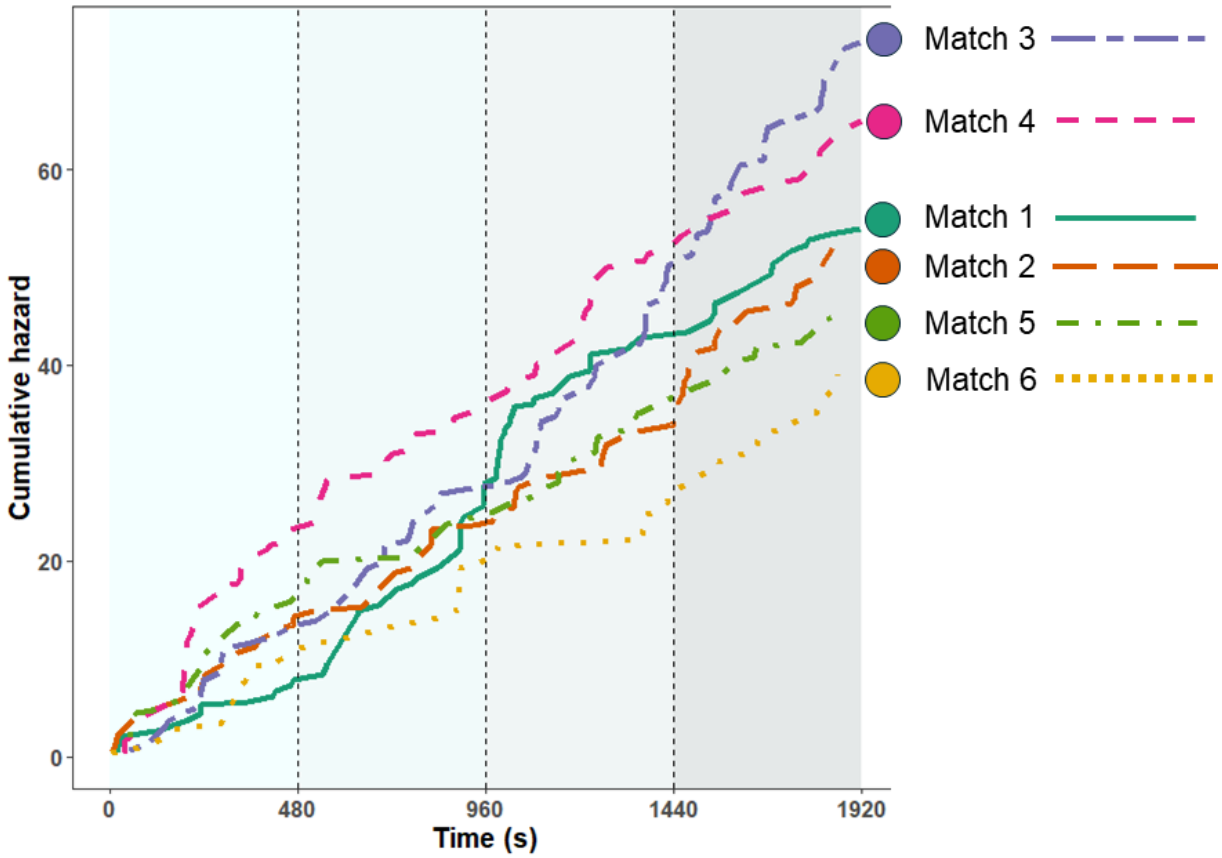

Figure 5.5. Cumulative hazard calculated for each of the six matches played by Team Canada. Curves are labelled according to the order in which matches were played during the tournament.

Players' self-reported ratings of fatigue confirmed that match play induced fatigue. There were also indications of accumulated fatigue during a tournament. The variability in ratings between players was interesting to note and echoed observations by Russell, Jenkins, et al. (2020) about the spread of subjective fatigue rated by female players before and after professional netball matches. Unlike studies in which fatigue is experimentally induced, the present case study took place during a two-week period of a real tournament. Thus, in addition to differences in playing time and in internal load, there were myriad other potential sources of variability. Players' personal sleep, nutritional, accelerated recovery methods, screen time, and coping behaviours are just some of the possible contributors to fatigue and vigor states. Furthermore, pre-match ratings of fatigue in the current study were higher, and change in fatigue accordingly relatively smaller, than reported among netball (Russell, Jenkins, et al., 2020) and volleyball (da Costa et al., 2023) players at competition. This was the team's first major international competition since the relative easing of COVID-19 restrictions, which presented limitations to training in the preceding year, and took place in a strict health and testing setting. Not being accustomed to the intensity of tournament play, in addition to managing the additional cognitive load of potential exclusion of the entire team from the tournament due to infection, may partially explain higher values of fatigue.

The analysis that combined the evaluations of offensive on-ball decisions of all teams and matches seemed to indicate a steady increase in the hazard of poor decisions as a match progresses (Figure 5.4A). Decreases in decision-making performance concomitant with increases in fatigue could be linked to detrimental changes in attentional control (Boksem et al., 2005), diminished emotional or impulse control (Russell, Jenkins, Rynne, et al., 2019), or a failure to adapt to fatigue-related constraints on action capabilities (Araujo et al., 2009), among others. Crucially, though, when examined from a larger perspective, the degree to which the hazard increased appeared negligible (Figure 5.4B), and the baseline hazard curves for the individual matches (Figure 5.3) highlighted that there is no universal pattern or profile. Additionally, the cumulative hazard of poor decisions for Canada's matches did not increase with each subsequent match. These findings may reflect the complex nature of team decision making, sport performance, fatigue and their relationships. This complexity was also exemplified in a study in which fatigue was induced using a 90-minute protocol designed to produce external and internal loads comparable to those elicited in matches (Teoldo et al., 2024). In small-sided games performed in a fatigued condition, male soccer players demonstrated both improved tactical efficiency in some aspects and reduced tactical efficiency in others, compared to the control condition (Teoldo et al., 2024). Nonetheless, there are also multiple examples of experimentally-induced mental fatigue being associated with impairments in on-field performance (Badin et al., 2016; Fortes et al., 2020; Trecroci et al., 2020). In contrast to the current study, though, fatigue was induced *prior* to playing small-sided games. Moreover, it is still relevant to note that the degree of mental fatigue induced by their cognitive task was higher than the pre-match to post-match change in the current study (Badin et al., 2016; Trecroci et al., 2020). Indeed, in the control condition, mental fatigue increased after playing the small-sided game. Yet, in the fatigued condition, players had greater levels of fatigue than the control condition both immediately after the cognitive task, as well as after playing the small-sided game (Trecroci et al., 2020), suggesting that the task may induce fatigue that is superior to fatigue that would develop naturally as a result of gameplay. Thus, in the context of fatigue developed during match play at competition, the change in perceived fatigue may not be as drastic as in experimental manipulations. Furthermore, experienced athletes may be more habituated with maintaining performance under familiar conditions of competition, compared to following a novel and/or decontextualized research protocol. These two points are especially relevant considering that mental fatigue often experienced by athletes "in real life" is the result of an accumulation of various factors, such as the demands of the elite sport environment, travel, and other broader sources (Weiler et al., 2024). In addition to differences related to how fatigue is induced and the timing of performance evaluation (e.g., pre-post or non-fatigue vs fatigued versus continuously over time), it is crucial to consider that there are typically much higher stakes associated with official matches compared to experimental manipulations or even simulated matches. Results demonstrating that male elite youth soccer players displayed different physical, technical, and tactical behaviours in official matches compared to training games (Olthof et al., 2019), and that male and female junior youth tennis players had different stroke rates and perceptual responses between competition and simulated matches (Murphy et al., 2016) may suggest that decision-making responses to fatigue also vary as a function of the performance context. Greater importance placed on the consequences of performance may be associated with altered patterns of play but also with higher levels of motivation which may influence perceptions of fatigue (Rubio-Morales et al., 2024) or offset negative effects of fatigue through tolerance of higher levels of effort (Barte et al., 2019).

Potential limitations of the current study included the sensitivity of the decision-making evaluation tool and the assessment of team rather than individual decision making. The decision-making scoring guide was structured to make the evaluation process as objective as possible. However, water polo remains a highly strategic sport that employs previously rehearsed sets of tactics and, as such, based on the team's specific system of play, there is greater nuance as to what constitutes a good or poor decision than what can be captured in a decontextualized scoring grid. As well, only on-ball offensive actions were judged, whereas defensive performance is also critically relevant in its potential susceptibility to impairment and subsequent impact on the outcome. Despite this, similar decision-making evaluations have been used previously in studies among soccer (Gabbett et al., 2008; Romeas et al., 2016) and volleyball (Fortes, Fonseca, et al., 2021) players to calculate a decision-making index (appropriate actions/total actions x

100%), which has displayed sensitivity to different experimental conditions. The nature of the analyses in the current study, though, which considered the team's decision making collectively, may not have captured declines in decision-making performance that occur on an individual level. Nonetheless, general limitations in the quantification of decision making, which often involve trying to distill a complex construct into a binary evaluation of discrete actions, should be highlighted. Even in cases such as the current study, which, notably, focused on fully embodied decisions (Raab & Araujo, 2019) in real competition games, it remains unclear how best to judge decision making accurately with consideration for the particular context in which players are acting.

5.5 Conclusion

This case study was the first to quantitatively assess decision-making performance during a real international competition to verify if it is altered as fatigue develops during a match and a competition. Through recurrent event analyses, using time as a proxy for fatigue, the results questioned the notion of universal decreases in decision-making performance as match-play fatigue develops. There was a general increase in hazard for poor decisions as a match progressed that appeared negligible when compared to the considerable variation observed among individual matches. Furthermore, the hazard of poor decisions did not increase with each subsequent match during the tournament. The contrast between the individual game models with the one that combined all games and teams parallel the significant individual, context-dependent differences – that exist despite general relationships – for exercise dose and response (e.g., Bouchard & Rankinen, 2001), or external load and internal load (e.g., Bartlett et al., 2017), among others. Therefore, it is highly relevant to consider performance on an individual- (game-, in this case) level rather than assuming that there is a consistent causal relationship between fatigue and decreased decision-making performance. Many other factors also play mediating or moderating roles – or may themselves be mediated or moderated by fatigue. In conceptualizing training objectives to optimize performance throughout matches and tournaments, fatigue associated with match play remains an essential variable to consider, but there would be value in taking a wider perspective and ensuring athletes are also prepared for other highly impactful features of the competition context (e.g., pressure, greater unpredictability, unfamiliar environments and opponents, etc.).

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Disclosure statement: The authors report there are no competing interests to declare.

Data availability statement: The data that support the findings of this study are available from the corresponding author, NB, upon reasonable request.

5.6 Supplementary material

Table 5.2. Descriptive statistics of offensive on-ball actions evaluated from six games played at the 2022 FINA World Championships

Game	Evaluated team	Total	Moves	Passes	Shots	Poor decisions	Good decisions as percentage of total	Goals
1	Canada	486	172	279	35	54	88.9	7
	Opponent	312	112	172	28	33	89.4	7
2	Canada	281	118	124	39	52	81.5	22
	Opponent	309	135	151	23	69	77.7	2
3	Canada	395	163	202	30	73	81.5	7
	Opponent	361	152	179	30	43	88.1	11
4	Canada	416	147	238	31	65	84.4	7
	Opponent	373	132	207	34	50	86.6	10
5	Canada	315	134	149	32	45	85.7	19
	Opponent	428	165	224	39	62	85.5	11
6	Canada	362	137	190	35	39	89.2	20
	Opponent	423	119	272	32	60	85.8	11

The results of the first four projects seem to imply that fatigue is not the only variable that is relevant to consider. Furthermore, there were learnings related to the importance of representativeness, from both our own work and the existing literature, that would be valuable to apply on the field. With this knowledge, the challenge became one of how to effectively translate it to practice to ultimately contribute to the development of more resilient decision making. Resilience can be described as a system's ability to persist or maintain function despite disturbances (Hodgson et al., 2015) and is a factor of the diversity, efficiency, adaptability, and cohesion of and within the system (Fiksel, 2003). Resilient decision making would thus involve sustaining performance in the face of different perturbations.

CHAPTER 6

THE CO-CREATION OF REPRESENTATIVE TRAINING DESIGNS IN ELITE WATER POLO USING A SCIENTIST-PRACTITIONER APPROACH

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6.1 Abstract

This article describes an evidence-informed, collaborative process to bridge the gap between science and practice and tailor representative training designs to a national water polo team. Team gaps and context-specific needs were identified and probed using quantitative methods and "gamestorming" focus groups. The resulting data informed the subsequent co-design of a Constraints-Led Holistic Approach to Overcoming Stressors (CHAOS), an intervention that considered not only physical, but also cognitive, and emotional demands of competitive match play. The process we depict may be adapted to diverse contexts, and we additionally share practical tools and reflections that may be relevant for other scientist-practitioners.

Keywords: co-design; integrated knowledge translation; representative learning design; constraints-led approach, embedded research

6.2 Science and practice in high-performance sport

Elite sport teams continually strive to improve, and the innovative and varied work produced by sport scientists generate intriguing potential avenues for performance gains. However, there still exists a dichotomization of science and practice – to the detriment of the impact of science on the field. Scientific research that is not informed by applied expertise can lead to addressing less relevant questions or making impractical recommendations, while field interventions that are not critically evaluated or evidence-based may be limited in their effectiveness or even harmful. In light of these challenges, an approach that embodies the scientist-practitioner framework (Schinke et al., 2024), in which research and practice reciprocally inform each other and data is gathered about the specific case of interest, offers a promising strategy. Additionally, ensuring that the approach is context-driven (Stambulova & Schinke, 2017) can have important consequences for the relevance, feasibility, and sustainability of a given intervention. Though there exist helpful recommendations and guiding points related to these frameworks (Schinke et al., 2024; Stambulova & Schinke, 2017), there are still few well-detailed, real-world examples available to practitioners and academics.

This article aims to contribute to filling this gap by sharing a concrete example of how the scientist-practitioner approach can be used to develop a context-driven intervention. We collaborated with Water Polo Canada to optimize competitive match-play performance of senior national team players. An initial identification of a performance gap (stage 1), and scientist-practitioner immersion within the local context (stage 2), were followed by a consultative process that combined applied expertise and scientific findings (stage 3). We discuss the first two stages briefly before focusing on the specific initiatives and tools used in the third, and ending with some reflections on the process. Ultimately, this example may generate ideas or depict a process that other practitioners and researchers may adapt to their specific contexts.

6.3 Initial identification of a performance gap and immersion within the local context

At Water Polo Canada, senior national team players typically play in professional or collegiate leagues abroad, centralizing for several weeks before major international competitions and during the last year of the Olympic quadrennial. The senior women's national team program is directed by team coaches, the main decision-makers for – and designers of – the team's training activities, who work with an integrated support team (IST). The IST consists of practitioners, sport scientists, medical staff, and administrative personnel who have a wealth of expertise in service delivery in high-performance sport and have experience, as staff and former elite athletes, with both water polo and other sports. During a team meeting aimed at identifying performance gaps, it was brought up that athletes' decision-making quality appeared to decrease over the course of match play, with fatigue being proposed to explain this observation. The crucial role of decision making for team sport performance, as well as lack of clarity in the scientific literature on how best to address the identified issue, led the first author to adopt this gap as the core research problem for her doctoral thesis. She, along with her two co-supervisors, made up the main research team. All three were familiar with the head coach and had previously conducted applied research with the same national team program.

As the first author's initial research work progressed from the laboratory to the field, she became an embedded researcher, leading activities within the team's training and competition environment. Travelling with the team to international competitions provided particularly rich insights about the context in which optimal performance is desired and about the complexity of the association between fatigue and performance. These on-field observations converged with the research team's original empirical research findings (Dong, Berryman, et al., 2024; Dong et al., 2022; Dong, Romeas, Filali-Mouhim, et al., 2024; Dong, Romeas, Vincent, et al., 2024) and the existing literature to reinforce that 1) while match play-related fatigue is relevant, it is one among many stressors that must be considered, and 2) representative designs should be a priority if the aim is to influence athlete performance during competitive match play. Indeed, the framework of representative learning design emphasizes that the training environment should represent the competition environment to maximize skill transfer (Pinder et al., 2011). Physical demands of match play are often replicated in training, but it is similarly crucial to consider the cognitive and emotional demands of competing (Araújo et al., 2020). One evidence-based method to enhance representativeness is by using a constraints-led approach (Renshaw & Chow, 2019), in which intentional training designs are created by manipulating individual, environmental, and/or task constraints. Consequently, rather than focusing exclusively on fatigue as a potential disruptor of performance, we believed it vital to take an approach that was more representative of the sport demands and that holistically considered other competition-specific factors (e.g., pressure, increased cognitive load). Therefore, our goal became one of creating an intervention based on a Constraints-led Holistic Approach to Overcoming Stressors (CHAOS).

6.4 Bridging science and practice

Although there is good agreement across different theoretical perspectives on the value of representative training (Lindsay & Spittle, 2024), meaningfully enhancing a team's existing training requires their buy-in and a deep understanding of their specific beliefs, needs and style of play. Consequently, we undertook a process of co-creation, which involved consultation with the team and the co-design of CHAOS. All activities were approved by the Comité d'éthique de la recherche (CERPÉ; 2024-5859) at the Université du Québec à Montréal. Athletes and staff provided written consent and had freedom to select the parts in which they wished to participate.

6.4.1 Conducting a needs assessment

Scientist practitioners can play a valuable role by systematically investigating a presumed phenomenon, adding a complementary angle to coach insight. Using both quantitative and qualitative approaches, we first conducted a gap analysis with the objectives of understanding key differences between training and competition demands and ensuring that the proposed intervention would be relevant and feasible. Working with Water Polo Canada athletes and staff, we combined research tools with interactive "gamestorming" techniques to co-create knowledge and integrate data from different sources.

6.4.1.1 Quantifying differences between competition and training demands

Twenty-six members of the women's water polo senior national team training pool (i.e., the group from which the players who represent Canada at international competitions are chosen) participated (age range at time of participation = 17.9-31.2 years). They reported their subjective competition and training loads using questionnaires at a total of four international competitions played between March 2022 and November 2023, within 20 minutes of the end of each match, as well as immediately after each practice during a two-week period of training in September 2023. Players' participation in filling out questionnaires varied depending on the makeup of the team roster and individual preferences. The questionnaires included a 0-100 visual analog scale (VAS) for mental and physical fatigue, which were operationalized as in Russell, Jenkins, et al. (2020); and the first five subscales of the NASA Task Load Index (NASA-TLX; Hart & Staveland, 1988): mental demand, physical demand, temporal demand, performance, and effort. For one competition, players marked their ratings for these constructs on printed-out paper versions of the VAS and NASA-TLX, and used their phones or a team iPad for the rest of the measures. The self-report data was categorized by context: whether it was from competition against higher-ranked opponents (top 8 globally), competition against lower-ranked teams, or regular training. A linear mixed model was used to compare the three contexts. Significant effects were followed-up with Bonferroni-corrected post-hoc pairwise comparisons of estimated marginal means. There was a significant interaction between construct and context ($F[12, 3328.9] = 7.38$, $p < 0.001$; Figure 1). Ratings were significantly greater for higher-ranked teams compared to regular training for all constructs except performance and post-event physical fatigue. For all constructs except performance, ratings were significantly higher for regular training and for high-ranked teams compared to lower-ranked teams. See Table 6.3 in Appendix A for detailed statistical results.

6.4.1.2 Discovering perspectives through "gamestorming"

Athletes' perceptions. The athlete session was moderated by the first author in her role as embedded researcher. It was emphasized that everything said would remain anonymous, including in the eventuality that content would be shared with staff. Three main points were discussed. First, athletes were asked "what about competition is challenging or different from regular practices?" and engaged in *Post-Up* and *Affinity Mapping* activities (Gray et al., 2010). Players were asked to think broadly and generate as many ideas as possible, writing down each one on a separate sticky note. Once it appeared there were no more new ideas, they stuck all their sticky notes onto the wall (*Post-Up*). Then, a group of players, with input from the others, rearranged the sticky notes into clusters based on the content and created a title/theme for each cluster (*Affinity Mapping*). The main clusters they generated are listed in Table 6.1.

Table 6.1. Ideas and clusters generated by the athletes in *Post-Up* and *Affinity Mapping* activities to describe aspects that differ between competition and regular training.

Cluster	Select sticky notes
Food	"Food" "Different food"
(No) Freedom	"Only thing that you do during your day, 0 balance" "Access to actual alone time" "Every minute of day scheduled" "Lack of control over your life"
Logistics	"Jet lag" "Shitty hotels (sleep)" "Being in a foreign place" "Travelling"
Distractions	"Referees" "Presentations/ceremonies"
(Lack of usual) Support system	"Being away from home/support people" "Not having support system (partner & animals)"
Different teams	"Opponents are more unknown than your teammates" "Playing against diff. tactics than our own" "Game situation (can't simulate that outside a game)"
Physical intensity	"Intensity" "Physical exertion is higher than practice"
The unknown/ unpredictability	"No control" "More things feel out of our control" "Changing tactics unexpectedly" "Unpredictable"
Cost of mistakes	"Making a mistake is a problem → in practice you learn, in game you do/act" "Less room for error & learning, everything has to be fixed instantly" "Losses from earlier in a tournament affet you"
Stress and pressure	"Stress" "High stakes/more competitive" "Performance + results that matters" "Gravity of the outcome" "Spectators or crowd/family at home watching"

Next, each player was invited to individually reflect and write down an experience where she felt underprepared for a game or competition, and one in which she felt well-prepared. The experience could be based on how she felt as an individual or as a member of the team and could be from any point in their water polo careers. One by one, each player shared two experiences. It quickly became apparent that there were key similarities in the experiences with which the players attributed under-preparation and good preparation. This exercise generated rich discussion among the team as players made links and related their own thoughts to the stories that their teammates were sharing. It appeared as though there were perspectives about their current training environment that had not been explicitly discussed as a team and that this exercise allowed the athletes to understand the extent to which some of their individual needs were shared across the team as a whole.

The last activity combined the "gamestorming" activities of *Plus/Delta* and *Dot Voting* (Gray et al., 2010). Working in three groups, the athletes were asked to add items they thought the team needed more of, or that needs to be added, in the "plus" column of a poster board. On the other half of the poster board, in the "delta" column, they were to indicate things that they believed should change. Once all groups were finished, they took turns presenting their ideas, which again generated discussion among the group. Next, the first author, using live input from the players, synthesized the three groups' work into ten points in a new plus/delta table. Participants then received five stickers for an adaptation of *Dot Voting*, with the instruction to indicate which items they thought should be prioritized by "voting" with their stickers.

During and after the session, players expressed the desire for the points discussed to be shared with coaches, prompting the first author to have a meeting with coaches. Although, going into the session, we expected to primarily be learning about athletes' experiences of competition to eventually inform how representative training designs should be oriented, it ended up also being a platform for the players to connect over, and align on, more immediate ways of improving their daily training environment and preparation for upcoming competition. This served as a good reminder that while we may be intent on enhancing performance through a particular approach, and even have good reasons to focus on that specific aspect, those at the core may perceive more pressing issues to address. We should actively make the time and effort to listen, since they may also be the ones with the solutions.

Staff perceptions. The session held with the staff was also moderated by the first author. As with the players, the first question the staff members were asked to think about was "what about competition is challenging or different from regular practice", and they were encouraged to draw from their experiences in different roles, e.g., as an athlete, coach, practitioner. Using *Post-Up* and *Affinity Mapping* as described earlier, the staff members, too, clustered ideas thematically (Table 6.2). They also identified relationships between the clusters, namely that "[e]verything can be a distraction in the end" and all the items can play a role in stress.

Table 6.2. Ideas and clusters generated by the staff in *Post-Up* and *Affinity Mapping* activities to describe aspects that differ between competition and regular training.

Cluster	Select sticky notes
Selection	"selection" "minutes in water"
Outcomes	"bigger focus on outcome" "no second chance" "mistakes are more 'risky'"
Environment	"food" "refs" "travel (jet lag, home sickness, different food, etc.)" "access to proper training venue, equipment & schedule" "cohesion; living together, playing together, winning or losing together"
Opponents	"opposition" "different styles of opposition (vs what we encounter in training)" "opponents that want to win" "different tactical situations"
Distractions	"transportation" "pressure of crowd, fans, family, (media) expectations & focus" "other coaches" "uncontrollable"
Stress	"stress" "anxiety" "sleep" "fatigue" "pressure" "recovering"

The other main part of the session involved the question "what is the biggest challenge standing in the way of Olympic qualification and success?" The high-level answer that was agreed upon was "consistency of performance", which was probed by following the essence of the *5 Whys* activity. With the objective to get deeper into root issues, starting with "*why* is performance inconsistent?", with each subsequent reason articulated, participants were asked *why* that was the case (i.e., what were the underlying causes). There was a divergence of opinion at the first "why", so we explored the layers of both branches. Once again, this opened up discussion on different but connected topics, including reflections on what is happening when the team performs well, and on the influence the staff may have.

6.4.2 Weaving data to inform practical intervention

The team's self-reported ratings (Figure 6.1) revealed that there were some maximal ratings of physical demand at practices, but that, in contrast to games against top-8 opponents, mental demand was never rated as maximal at regular training. This appeared to corroborate themes that emerged in the focus groups, particularly ideas related to the unpredictable and high-pressure nature of competition gameplay. To the players, in competitions contexts, there are many aspects outside of their control, and they must often adapt to unpredictable situations in and out of the pool. Both players and staff highlighted that in addition to higher intensity of game play, there is an omnipresent sense that the outcomes matter, as well as various internal and external distractions to manage that are atypical of the daily training environment. Indeed, flexibly adjusting the game plan and self-regulating in high-stakes conditions against unfamiliar opponents is highly mentally demanding. The athletes evoked previous negative experiences with being expected to change their strategy without advance warning, as well as the importance the team placed on being unified tactically, while the staff highlighted the few opportunities, compared to other teams of similar calibre, available to them to compete against high-quality opponents. In this way, various sources of data (i.e., practical expertise from athletes and coaches, our research activities, and the existing scientific literature) were integrated to focus the objective of CHAOS to one of tailoring representative training designs to provide opportunities to target tactical objectives while requiring players to adapt quickly and appropriately as the situation unfolds. Combining this with pressure training (Low et al., 2023) would allow athletes to practice performing under anxiety-induced alterations in perception, cognition, and motor abilities; as well as applying appropriate coping skills.

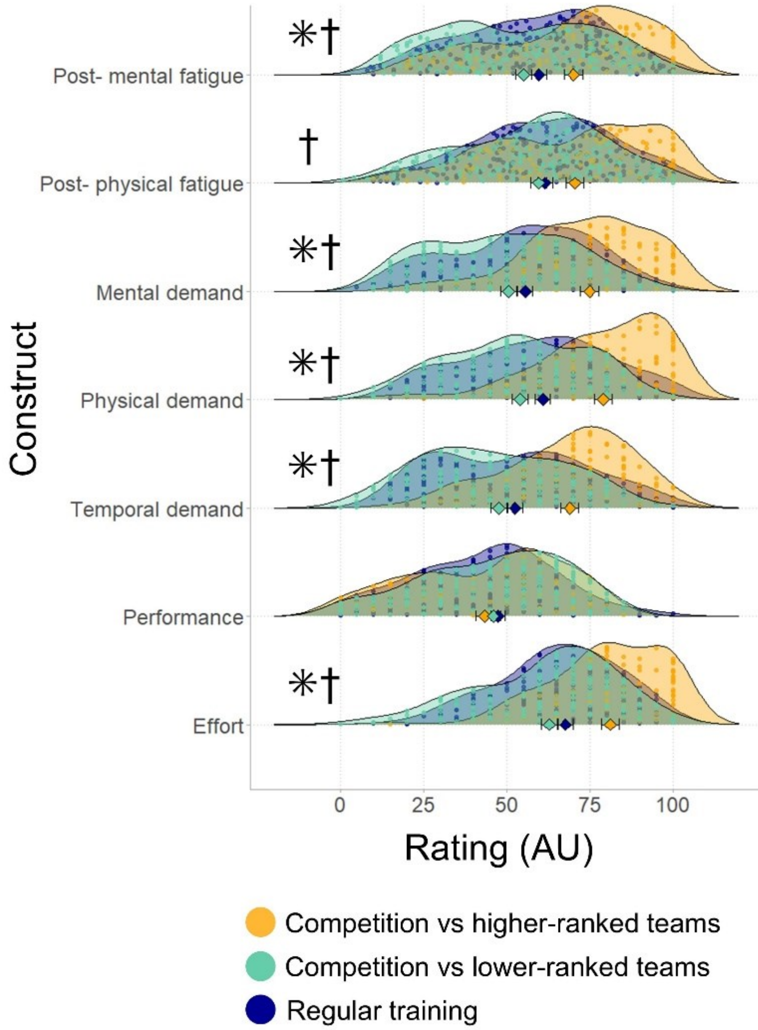

Figure 6.1. Distribution of post-event self-reported measures. Diamonds represent estimated marginal means ± standard error. ∗ indicates significantly lower ratings for competition against lower-ranked teams compared to high-ranked teams and to regular practice. † indicates significantly lower ratings for regular training compared to competition against higher-ranked teams.

6.5 Co-designing CHAOS

Shortly after the initial "gamestorming" sessions, a meeting was held with seven staff (composed of Water Polo Canada coaches and IST members) and the main research team, moderated again by the first author. First, a synthesis of the needs assessment was presented, with an emphasis on how it refined the objective of CHAOS. Greater theoretical background for representative design and the constraints-led approach was then introduced to give the group a common language and understanding for subsequent discussions. We next oriented towards generating ideas, starting with an exercise based on *Brainwriting* (Gray et al., 2010). Thinking about the physical, mental, and emotional demands of competition, everyone was asked to write down as many ideas as possible about how to increase the representativeness of training during either a specific drill or an entire practice. After an initial period to write down each idea onto a separate sticky note, each person passed their stack to the left and had one minute to elaborate on, or write down additional ones inspired by, the new ideas in front of them. This rotation continued until everyone received their original stack back, at which point participants were requested to place each of their sticky notes somewhere in a three-circle Venn diagram that had one circle for each of physical, mental, and emotional dimensions. Concepts of fidelity and demand (Champion et al., 2023), and the balance of how game-like a drill is with the workload associated with it, were then presented. This led to the next exercise in which, each participant picked two sticky notes from the Venn diagram, and, in two groups, identified ways in which the load associated with the idea on the sticky note could be increased and decreased. Lastly, the groups were presented with two of the team's real tactical objectives and asked to generate ideas of drills that could be used to address them.

In the following weeks, members of the research team met to brainstorm training designs based off the ideas generated with the staff. Following iterative pilot testing and additional observation of regular practices, we identified minor modifications to existing drills as well as proposed a set of exercises that each targeted a specific team tactical principle/objective. In the latter designs, task constraints (e.g., rules, point systems, number of players) were used to encourage or focus on certain actions, without removing completely other possibilities. Through one-on-one meetings with coaches to explain the designs in more depth and gather their feedback, refined versions were developed. See Appendix B for an example of one of the proposed training designs.

6.5.1 Undesirable CHAOS

Shortly after, we encountered unplanned, uncontrolled chaos in the forms of a fire at the team's training facility a few months before the Olympics, its subsequent long-term closure, and the consequential hurdles related to regular contact between the research team and the team staff. This event compounded the already existing challenges of innovation during Olympic preparation and reduced opportunities to work with the team due to their significant time abroad at training camps. Later discussions would indicate that certain ideas and concepts proposed within the CHAOS process were indeed integrated regularly within the team's training. However, in the end, there was no opportunity for the main research team to participate in systematically testing, refining, integrating, and evaluating the new exercises, nor to implement pressure training. Similarly, informal discussions with coaches supported that the work produced by the project was highly relevant and practically applicable, but plans to collect feedback from athletes and staff through interviews, focus groups, and/or questionnaires were not realized. Despite a deviation from the intended course, the value that the coaches ascribed to the designs as well as the willingness and desire to integrate CHAOS within their training plans suggest that this process and collaboration were nonetheless constructive.

6.6 How can you create CHAOS?

A question we have often been asked is how others can incorporate CHAOS training. There is no simple answer, but we believe that the context-dependence and open-endedness is actually one of the strengths of CHAOS. The basis of CHAOS is to consider the physical, cognitive, and emotional demands of performance and pragmatically use principles such as the constraints-led approach to enhance representativeness of training, thereby contributing to optimal competition preparation. The exact priorities and designs will depend on the local context. In our case, the first step was to identify priorities through immersion in the team context and a multi-dimensional consultation process, in which we collected team-specific data and sought insight from athletes, staff, and researchers. This informed the subsequent intervention, which was further tailored to the team and its playing objectives through an iterative and collaborative design phase. The activities we described within this approach, of conducting a needs assessment and engaging in collaborative conception, provide just one example of how such a process could look: ultimately, the "how" that is most appropriate will be a function of the "who", "when", and "what (goals)". To complement the description of our co-creation process, as well as the practices, values, and recommendations synthesized for the scientist-practitioner model (Schinke et al., 2024) and for context-driven practice/intervention (Stambulova & Schinke, 2017), we share some reflections based on this experience:

- "*Science*" *can and should be adaptable:* In contrast to some traditional conceptions of research protocols, our methods were open to change to ensure practical feasibility. For example, based on athlete and coach feedback, the format of delivery, as well as the questions used in the questionnaires evolved. The first author also met with athletes individually to adjust their participation if needed. This sensitivity to the context and openness to negotiate is what allowed research activities to occur at such events as the World Championships and the continental Olympic qualifying tournament. During the athlete "gamestorming" session, there were also spontaneous adjustments, allowing the group to steer the direction and focuses of the discussion. This led to important opportunities to support immediate changes in their daily training environment – as well as potentially even unintentional teambuilding.
- *Control is not a given:* In elite sport, limited time and resources, pressure to succeed and fluctuating risk tolerance, as well as concentrated decisional power contribute to the volatility of the support and opportunities for research and intervention. We had several activities – that were relevant and co-conceived – and that were started and not carried out as envisioned, or not initiated at all. Circumstances or outcomes outside of our control can be an invitation to remain understanding of the training context (e.g., an upcoming competition and reduced willingness to engage with novelty), resource availability, team attitude, and different or bigger priorities, and focalize energy on the core, essential aspects.
- *It takes a team:* Collaboration was an important theme of this work. There was a wealth of complementary practical experience among the coaches, athletes, IST, and research team, combined with scientific expertise that spanned various disciplines. Translating this into the development of a practically relevant intervention required significant trust. This, and the interpersonal relationships fostered through the research team's work prior to this project, their familiarity with the culture, and immersion within the team context were foundational to the subsequent consultation process and intervention design. In our experience, the alignment and explicit support of others was also critical. There were key moments in which the championing by other members of the research team was pivotal to convince decision makers of the value and credibility of proposed initiatives or components. Furthermore, actions taken by the IST lead to

give space for project updates at every IST meeting place importance on and lent legitimacy to the ongoing initiatives, while reinforcing the collaborative nature of the project.

6.7 Conclusion

High-performance sport can be a dynamic, complex environment in which it is sometimes unclear how best to contribute to optimizing performance. Through co-creation and the inclusion of both scientific approaches and practical expertise, it is possible to combine athlete, staff, and researcher perspectives and ultimately generate context-relevant and evidence-based recommendations for practice. In sharing our experience, which revolved around enhancing representative training among an elite water polo team, we hope to have provided ideas of methods and specific tools that scientist practitioners can use to address performance challenges within their unique contexts.

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Declaration of interest: The authors declare that they have no conflicts of interest.

Data availability statement: The quantitative data that support the findings of this study are available from the corresponding author, TR, upon reasonable request.

6.8 Appendix A

Table 6.3. Estimated differences in ratings of self-reported internal load constructs indicated by athletes after competition games against higher-ranked teams, against lower-ranked teams, or after regular training

Construct	Comparison	Estimated difference ± SE [95% CI] AU	p
Post- mental fatigue	Higher-ranked - lower-ranked	15.26 ± 2.56 [9.07-21.45]	< 0.001
	Higher-ranked - regular training	9.04 ± 2.54 [2.97-15.12]	0.001
	Regular training - lower-ranked	6.21± 2.12 [1.14-11.28]	0.010
Post- physical fatigue	Higher-ranked - lower-ranked	11.30 ± 2.59 [5.11-17.49]	< 0.001
	Higher-ranked - regular training	6.08 ± 2.54 [0.002-12.16]	0.050
	Regular training - lower-ranked	5.23 ± 2.12 [0.16-10.29]	0.041
Mental demand	Higher-ranked - lower-ranked	24.48 ± 2.59 [18.29-30.68]	< 0.001
	Higher-ranked - regular training	17.82 ± 2.52 [11.79-23.85]	< 0.001
	Regular training - lower-ranked	6.66 ± 2.09 [1.65-11.67]	0.004
Physical demand	Higher-ranked - lower-ranked	24.94 ± 2.58 [18.76-31.13]	< 0.001
	Higher-ranked - regular training	18.07 ± 2.52 [12.04-24.10]	< 0.001
	Regular training - lower-ranked	6.88 ± 2.09 [1.87-11.88]	0.003
Temporal demand	Higher-ranked - lower-ranked	21.59 ± 2.58 [15.40-27.78]	< 0.001
	Higher-ranked - regular training	14.51 ± 2.52 [8.48-20.54]	< 0.001
	Regular training - lower-ranked	7.08 ± 2.09 [2.07-12.08]	0.002
Performance	Higher-ranked - lower-ranked	-2.92 ± 2.58 [-9.10-3.27]	0.778
	Higher-ranked - regular training	-1.11 ± 2.52 [-4.92-7.14]	1.000
	Regular training - lower-ranked	-1.81 ± 2.09 [-6.81-3.20]	1.000
Effort	Higher-ranked - lower-ranked	18.29 ± 2.58 [12.11-24.48]	< 0.001
	Higher-ranked - regular training	12.94 ± 2.52 [6.91-18.97]	< 0.001
	Regular training - lower-ranked	5.35 ± 2.09 [0.34-10.36]	0.032

6.9 Appendix B

Example of co-created training design.

Roulette

General objective

Promote versatility without abandoning the expectations and anticipations related to opponent-specific tactical tendencies.

Basic concept

There are two teams, with one playing in the style of an opposing team. The total number of reps is known. The "opposing" team must act according to their assigned country for the majority of the reps (i.e., follow their typical system and expected response) and act "atypically" for the remaining reps to try and trick the other team ("Canada"). The "opposing" team is told by the coach how many of the reps must be "typical", but team "Canada" does not know this exact number – they only know that it will be most of the reps.

Example 1

Tactical focus: Drive offense versatility

Field size: Half-court, 1 net.

Rules: Each of the two teams runs 10 reps as offense and 10 reps as defense. When on offense, they play as Canada, and when they are on defense, they are a specific rival country (for all 10 reps). Before beginning, each team is told how many times out of 10 that they, when on defense, must defend following the typical response of their assigned country (between 6-8). Neither team knows the number given to the other team, only that the other team will perform as expected "most of the time" (for more than 5/10 reps).

→ In real life, there is an anticipated response to a drive based on the opposing team and their tendencies. We are preserving that reality, while also emphasizing that the anticipated response is not a certainty and the attacking team must be ready to adapt.

During each of the reps, the attacking team must drive. The defending team is allowed to strategize together before each rep to decide how they will respond ("typical" or "atypical", and if atypical, how): in other words, they can decide the order in which they play typically and atypically, staying within the limits of their assigned number (e.g., 7/10 must be "typical", leaving them the freedom to try something different to throw off the attacking team for 3/10 reps).

There are 18 seconds on the shot clock for each rep. The attacking team gets 1 point for each goal. The defending team gets 1 point for each steal or if there is no decent shot attempt by the attacking team.

Desired stable outcome: The attacking team is able to adapt appropriately when the defending team does not react as they expect. Bonus outcomes: developing greater familiarity with opponent defensive systems through role-playing.

Other constraints that could be manipulated:

- Possession time
- Number of reps and sets (e.g., becoming a different country for the next set), or using a set number of points as the objective (e.g., first team to 10 points)
- Net size and presence of goalie
- Further task rules and/or how points are allocated

CHAPTER 7

GENERAL DISCUSSION

Sparked by practical concerns for water polo match-play decision-making performance and spurred on by gaps encountered in the existing scientific literature, this thesis examined questions related to decision-making assessments, the exercise-cognition relationship, the effects of fatigue, and the co-design and implementation of more representative training. The diversity and depth of the expertise of the core research team in themes such as physiology, cognition, skill acquisition, and applied sport science was enhanced by an openness to multiple theoretical perspectives. Consequently, our research questions were refined – and our approach adapted – throughout the process, even if it involved straying beyond comfort zones. In our first experimental study, we aimed to evaluate the construct validity and test-retest reliability of a video-based task designed to test water polo decision making skill. We next examined performance on this domain-specific test, as well as on a domain-general Stroop test, during exercise. In this second study, we were interested in understanding how performance on both cognitive tasks may be affected by exercise intensity, modality, and duration. In parallel, we conducted a scoping review to synthesize what is known about the effects of fatigue on perceptual-cognitive performance, a skill underlying match-play decision-making performance, among open-skill sports athletes. Transitioning to the field, our next project had the goal of assessing decision making during a water polo tournament and investigating how the hazard of making a poor decision evolves over the course of a match and of a tournament. The first four projects explored various fields of study, research methods, and opened multiple possible strategies to intervene. This process led us to ultimately choose, for the final project of this thesis, the objective of helping players develop more resilient decision making through the integration of more representative training. Remaining agile in our attitude allowed us to incorporate new knowledge as it emerged, orienting and informing more relevant subsequent approaches, and made it possible to engage in the integrated knowledge translation process – both defining features of this thesis. Collectively, the projects in this thesis generated important, new scientific knowledge; prompted reflections on integrated knowledge translation within high-performance sport; and revealed potential avenues to maximize the impact of integrating representative training to develop resilient match-play decision making.

7.1 Significant contributions

Though the importance of decision making for sport performance is universally acknowledged, there is no consensus on the best strategies to measure it. We added to a growing body of work that questions the validity of sport-specific video-based tests, the most commonly used tool for assessing athletes' decision-making skill (Iskra et al., 2024). We found that a water polo video-based test that was not highly representative could not discriminate among athletes who had already achieved a high level of performance, challenging the use of such paradigms for talent selection in these groups. Currently, coaches rely heavily on their subjective observations to judge the degree of learning or progression in athletes' decision making-related skill acquisition. Accordingly, a more standardized method would be of value. However, we quantitatively demonstrated that performance on the video-based test improved from one week to the next, indicating insufficient reliability to detect meaningful changes in performance over time. Nonetheless, our practical and time-efficient (i.e., testing the whole team at the same time), low-technology protocol, with its unique gamified nature, had a format that could still be useful from other perspectives. Video analysis sessions are common practice in water polo for discussing both the team's and opposing teams' tactics, and there are opportunities to more actively engage athletes via a similar continuously interactive format. This could contribute to achieving objectives related to developing athletes' game knowledge while providing coaches with an idea of what is understood or not – at least in a declarative sense. Our results do not conclusively dismiss the utility of video-based tests for comparing athletes' decision-making skill or monitoring progress, but rather support that care needs to be taken to use representative designs (Araujo & Davids, 2015). The representativeness of the stimuli presented to athletes may be especially important (Kalen et al., 2021) – though perhaps among elite athletes in particular, including sport-specific responses would be an important consideration for the validity or sensitivity of a decision-making test. Indeed, researchers have suggested that since athletes' decision making during match play is dynamic and involves a high level of cognition-action interaction, not only should decision-making tests feature more representative stimuli, but they should evaluate movement execution and consider using self-paced responses to allow athletes access to emerging options (Iskra et al., 2024). While there are challenges in creating video-based tests with representative stimuli and responses for an aquatic sport, 360VR training methods for water polo goalkeepers exist as promising examples (Richard et al., 2021).

Decision making is commonly thought to be negatively affected by match play-related fatigue, but there exists little empirical work specifically investigating this relationship. In our case study that examined Canada's performance at the 2022 World Championships, we revealed new insights about water polo competition match play as well as about the evolution of decision-making quality. For the first time, we quantified the number of on-ball decisions that are made during a match, as well as the perceived loads associated with international tournament games. Our work also used a recurrent events approach in a novel way to consider time as a continuous variable and model the hazard of poor decisions across a match and a tournament. By applying piece-wise exponential additive mixed models, we identified a steady increase in hazard over the course of a match that appeared, however, to be trivial when considering the highly idiosyncratic shapes for hazard of the individual games. Combined with the lack of a distinct increase in poor decisions as the tournament continued, this highlighted that match-play fatigue is not invariably reflected by decreased decision-making quality. Though we were constrained by resources, the degree to which the hazard functions are representative of the teams' performance could be enhanced by the inclusion of more games, as well as evaluations of defensive actions, in the models. Assessing individual decision making – rather than team decision making, as was the case in our study – and its evolution throughout a match and a tournament, in conjunction with subjective self-report data, would provide an interesting supplemental perspective. While time-intensive, this type of investigation could be made more feasible through the integration of human and technological resources, such as in the application of team-specific computer vision algorithms accompanied by human judgement for less straightforward situations.

Notably, the findings of this thesis also extend beyond the realm of water polo to contribute to more general scientific understanding about the exercise-cognition relationship. Using a dual-task protocol, we specifically targeted gaps related to athletes' cognitive performance under different exercise conditions (i.e., continuous moderate intensity and continuous and interval high-intensity), for different types of cognitive tasks (i.e., domain-general and domain-specific), and how it may be influenced by exercise duration. Our work reinforced that the effects of exercise intensity on simultaneous cognitive performance are specific to the participant sample and the cognitive processes being solicited (Browne et al., 2017; Cantelon & Giles, 2021). Furthermore, we generated original insight, revealing that there were no differences in accuracy, reaction time, and self-perceptual responses between a continuous and an interval high-intensity exercise condition, and that exercise duration may indeed be an important factor in exercise intensity-related decrements in executive functioning (Schmit & Brisswalter, 2020). As the first to include both a domain-general and a domain-specific cognitive task performed during various exercise conditions, we found fascinating differences for both behavioural and self-perceptual measures. There were significant exercise intensity-related effects on reaction time for the domain-general task only, in addition to a positive correlation between affect and accuracy. Additionally, the athletes rated perceived effort, mental demand, and physical demand higher for the domain-general task than for the domain-specific task, despite identical exercise protocols, supporting the relevance of questions about how domain-specificity (Kalen et al., 2021) fits within the context of exercise and cognition. Since our experimental design was insufficient to ascertain if differences between the tasks were linked to the domain-specificity of the task or primarily to different cognitive functions solicited by the tasks, incorporating brain imaging techniques would help to begin answering this question, as well as potentially provide mechanistic insight on the exercise intensity- and duration-related effects. In parallel, studies designed to investigate dual-task performance that include cognitive tasks that require, predominantly, distinctly different cognitive functions could help reveal the extent to which the exercise-cognition relationship varies according to the specific cognitive function being tested. Moving forward, researchers could also consider having exercise conditions continued to exhaustion and conducting time-series analyses of simultaneous cognitive task performance to generate further understanding on the temporal dynamics of cognitive functioning during exercise.

Our scientific contributions involved generating new findings, but also revealing the limitations of our collective scientific knowledge. In our scoping review, we aimed to describe existing knowledge about how fatigue, a prominent perceived disruptor of decision-making performance, affects perceptual-cognitive performance among open-skill sport athletes. Our mapping of the literature included identifying how fatigue is induced and how performance is assessed. We found that fatigue was associated with worsened perceptual-cognitive performance, but also with improved and no change in performance. There is increasing interest in how fatigue influences sport performance, but current knowledge is derived predominantly from studies with male participants and non-sport-specific fatiguing and/or perceptual-cognitive tasks, and in which the induction of fatigue and assessment of task performance are sequential rather than simultaneous. Our results bolster other calls for increased female inclusion in sport science research (e.g., Cowley et al., 2021; Martinez-Rosales et al., 2021) and sport-specific, representative designs (e.g., Iskra et al., 2024; Thompson et al., 2019).

Finally, we both used and translated research in a more practical setting in our endeavour to integrate more representative training and facilitate the development of more resilient match-play decision making. Taking a co-creation approach, we quantitatively sought athletes' perceptions but also applied "gamestorming" strategies for research purposes to enrich our understanding of the situation from both staff and athlete perspectives. The practically-relevant co-designed training drills reflect the synergy that is possible when staff and athletes are involved in exposing challenges and contributing their insight. Importantly, in instances such as when I shared with coaches the needs the athletes had identified, we demonstrated how optimizing the value of research for practice involves maintaining a critical and flexible spirit, adapting to the emerging situations. Although contextual factors prevented us from implementing structured pressure training in conjunction with the more physically- and cognitively- representative designs, targeting the emotional component of representativeness would add immense value to holistic competition preparation.

In parallel to these project-specific highlights, a consolidated perspective of our work emphasizes the complexity of measuring decision making, the complexity of psychophysiology, and reveals an approach based on theoretical, empirical, and practical convergences. In our scoping review, we identified different ways by which researchers have tried to quantify decision-making performance, and highlighted the lack of any standardized method, but also the extent to which parameters vary between protocols. We used two common assessment strategies in two of our original studies, with the results of the video-based test indicating that a task that requires a passive response to third-person perspective, non-immersive videos is not well-suited for measuring match-play decision-making skill. Subsequently, the evaluation of decision making during competitive matches captured athletes' behaviour in its natural setting, but the broader process also revealed limitations related to how to define "objectively" a good versus a poor decision, as well as the challenge of assessing off-ball and defensive actions – not to mention the impracticality of the resources required for this time-consuming method of judging decision making play by play. Questions surrounding the quantification of match-play decision making are further complicated by the existence of differing theoretical models of decision making. Our review and our original research also pointed to the context-dependence of performance during simultaneous cognitive and physical exertion, with our laboratory work further reinforcing that many variables may play influential roles in how performance changes and for whom. Furthermore, continuing to probe self-perceptual aspects may offer potential avenues for mechanistic understanding of these relationships. Indeed, in addition to our empirical findings of different self-reported subjective measures for two cognitive tasks performed during identical physical exercise protocols, our scoping review and recurrent events analysis of decision making on the field suggested non-systematic effects of fatigue, thus strengthening the argument for the consideration of emotional and psychosocial contributions. Lastly, adhering to our objective of using research to ultimately inform and orient action, we navigated these complexities to find points of convergence among existing knowledge, our newly generated results, and the practical realities of working with an Olympic sport program. Integrating the commonalities of different models of decision making with our overall conclusions and the context of our relationship with Water Polo Canada led us to targeting enhanced representative design – implemented through a collaborative process with athletes and staff.

7.2 Integrated knowledge translation

An overarching objective of this thesis was to generate and use research to guide an intervention that addresses an applied scientific problem. As our work progressed from the laboratory to the field and my role from outside to embedded researcher, I gained more technical knowledge, developed a nuanced understanding of water polo and Water Polo Canada as an organization, and built solid relationships – all characteristic aspects of the initiation phase of integrated knowledge translation (Leggat et al., 2021). Combined with the evolution in our theoretical perspectives, these transitions compelled us – and made it possible – to continue pushing the limits of our expertise and comfort zones as we adopted the collaborative and malleable approach for the creation of CHAOS. From this perspective, it seems relevant to discuss not just the traditional research output of this thesis, but also how the activities of the first four projects laid the foundation for transforming research to action.

7.2.1 Initiation: Building relationships and gaining insight

When creating the video-based test, we worked directly with national program team coaches who selected game situations and identified the good, acceptable, and poor decisions for each clip. They were again heavily involved for the adaptation of the decision-making evaluation guide that was later used to evaluate match-play offensive on-ball actions of tournament games. The discussions with coaches and the challenges they brought up provided early indications that we should question the purposes for which these methods are and are not appropriate. In particular, coaches noted the difficulty in assessing decisions without the context of the team's and the opponent's systems of play. This contributed to our decisions, as a research team, against further exploring ways to quantify decision making and the influence of experimentally-manipulated variables, and ultimately oriented us towards more representative approaches to enhance decision-making resilience.

Whereas the sessions for the video-based test provided the opportunity for the athletes to get familiarized to me and for me to introduce the objectives of the thesis, the activities related to implementing self-reported load questionnaires at competition were pivotal to establishing a sense of trust. It was a priority to individualize the delivery of the questionnaire as necessary, according to each one's preferences; emphasize the anonymity of the responses; and reaffirm that participation could be withdrawn at any time. These steps were vital to the practical feasibility of collecting these data, but to the quality of the responses, too, by allowing athletes to feel confident that their participation could not have any bearing on coach decision making. Arriving to the point of administering research questionnaires at international competitions, though, involved multiple negotiations with the coaches. During this process, I gained important insight into the decisional power among elite sport teams – namely, that it is concentrated upon the coach – how to navigate the social hierarchies, and the need for vocal support from key people of higher status. It was also a chance to underline that our proposed ideas always had the athletes' wellbeing as a priority, rather than pursued research goals at the potential expense of performance. To ensure that the questionnaires would be duly completed at competition, we deemed it necessary for me to travel with the team to competitions. Once again, the value of this experience went beyond that of ensuring methodological consistency. In addition to providing me with an incomparable understanding of the larger context of water polo competition and the demands that athletes face during and outside of matches, team travel was critical in further connecting with the staff and athletes. These positive relationships and demonstrated consideration for applied context made it possible to continue incorporating research activities at subsequent competitions.

7.2.2 Special considerations for the high-performance sport context

While collaboration is core to the approach of applied sport scientists and practitioners, there are few documented examples of integrated knowledge translation in high-performance sport, where an embedded *researcher* works with main stakeholders throughout the research process. High-performance sport is a different environment than healthcare, where integrated knowledge translation – or at least the application of research to practice – is more frequently discussed. A synthesized reflection of the process within a high-performance sport context reveals unique challenges and benefits associated with my position as a student researcher, the complexity of navigating boundaries in embedded research, and special considerations for how success is defined in integrated knowledge translation.

Despite having had previous interactions with Water Polo Canada staff and athletes, in the context of this work, I entered their environment as a PhD student, without a formal position on the integrated support team or professional title. I was in essence an "outside" researcher, and despite my immersion and integration with the team in later stages of my thesis work, due to these circumstances, there remained a certain distance from the team. Challenges associated with this dynamic included less credibility in the eyes of the staff – and perhaps the athletes – missing relevant information about the team (e.g., athlete availability, changes in plans), limited communication access to staff and athletes, uncertainty related to my social standing, and high mental loads associated with navigating power imbalances. There were, however, also benefits of my unique role. Because I was not employed by Water

Polo Canada or as a performance services provider to the team, I had fewer conflicts of interest and did not report to coaches or other staff. I believe that being perceived as a "neutral" party, a role that I emphasized through my actions and verbal reminders, helped the athletes feel comfortable about being honest when filling out questionnaires and when participating during the "gamestorming" session.

In the context of high-performance amateur sport, in which resources are often insufficient, being an embedded researcher also brings up questions of which boundaries can and cannot be crossed. In our particular case, with the money supporting my work coming from research funds, with no other precedent to follow for the degree of embeddedness, there was great care to distinguish between research and services and specify that the scope of my duties would exclusively include predefined research activities. Drawing and communicating limits is essential to ensuring the researcher is not exploited (deliberately or not), but also to bring clarity to roles and expectations. However, they can also become restrictive, potentially confining the researcher's role – or perceptions of their role – to that of an outsider. Occupying this status can make it harder to integrate within the team and diminish the rate at which trust and confidence are established, with possible consequences for buy-in and researcher credibility later on. Greater thought into the implications of the research-service divide, along with more flexibility in the distinction, could be beneficial for all involved. The sport organization or team, perceiving immediate benefits associated with the participation of the researcher, may be more willing to commit in research initiatives. A well-embedded researcher and more engaged team may increase the likelihood for the project to be successful and accordingly, for prolonged or future interest in integrating research on the field. Nevertheless, when working with both athletes and staff – who inevitably experience a power hierarchy – the researcher acquires data/insight that may be perceived as sensitive, and it is a delicate balance to find between outsider neutrality and integration.

High-performance sport, and the research that occurs in this environment, are often characterized by clearly identified objectives, deliverables, and deadlines. In comparison, the conditions of collaborative research approaches can make these standards more challenging to meet. This was evident when contrasting the first four projects with the design and implementation of CHAOS. Research with humans, and arguably, especially when the participants are elite athletes, will rarely go exactly as expected.

However, even while adjustments will be inevitable, in traditional “researcher-driven” research, it is possible to create and follow a protocol, striving for a specific set of expected results. The success of the project is evaluated based on if the protocol was followed and if the intended type of results is obtained (regardless of the direction). This was the case for the three experimental studies and the scoping review. The significant differences in methodology, objectives, and researcher roles for the creation of CHAOS may justify different ways of operationalizing success for collaborative research. Unlike in traditional research, where the researcher is the primary decision maker, integrated knowledge translation deliberately seeks to engage research users throughout the process. In our situation, the coach, who was also the main knowledge user, held the power to direct where the project could go and when. Occurring over a long-term period in the “real world” rather than in the laboratory or during a concentrated period of time, initiatives were vulnerable to changes within and outside the sport organization. Furthermore, creating something of maximal practical relevance relied on adapting to emerging priorities and incorporating newly generated knowledge and understanding, making it unrealistic to outline precise predictions of expected research output. In light of these factors – which also lend themselves to the value of integrated knowledge translation – it would be beneficial to consider an operationalization of success that mirrors these differences from traditional research. The expectations that are set will be context- and project-specific, and while they can still be well-defined, should be tolerant of the uncertainty in the protocol and in the deliverables. Ideally, the reality of unpredictability should be understood and accepted by all stakeholders, including funding bodies who, in high-performance sport, are more familiar with supporting traditional research.

It is worth acknowledging that my experience was shaped by a unique blend of contextual factors, and that the process, challenges, and outcomes will differ by varying degrees depending on the people involved (including the embedded researcher[s]), the resources available, the risk tolerance, the sport culture and organizational structure, and the perceptions of research, among other variables. Accordingly, there will almost certainly be different experiences for different sports, financial margins (e.g., amateur vs. professional sports), and whether or not there is a culture that values or normalizes research. Nonetheless, I think it would be reasonable to expect that, across high-performance contexts, it is likely important to allow for flexibility in the roles we occupy; to be agile in the face of inevitable unanticipated situations; and to have influential people within the organization that support research, but also to engage the coaches and athletes to the extent that is possible.

7.3 Further research for more effective integration of representative training

When harnessing research for action, an important objective is to introduce initiatives that benefit performance, health, and/or wellbeing. Within the context of introducing more representative training to develop decision-making resilience, two applied research components that were not included in this thesis – but that could be relevant to achieving this aim – are 1) the intentional integration of the intervention within the team's broader training plan and 2) the assessment of its effectiveness. Although I propose some potential methods suitable for these two elements, there are also specific considerations related to the application of research in elite sport that are important to discuss.

With representative training, the focus is often on the fidelity of the training design, i.e., how game-like it is. However, the physical and cognitive loads that are associated with representative training should not be overlooked (Champion et al., 2023). While there is widespread agreement that representative training is crucial for improving performance during competition, high-fidelity exercises or sessions often also impose high loads. Concordantly, an integrated periodization approach recognizes the multiple dimensions of performance preparation, including skill acquisition, and the need to consider the contributions of all aspects to total training stress when designing and adapting programs (Mujika et al., 2018). Modulating physical training load with intention is important to avoid increasing injury risk, unintentional overreaching, or overtraining, as well as planning the timing for peak performance. In parallel, according to more holistic perspectives of training loads (e.g., Champion et al., 2023), mental (i.e., cognitive and emotional) loads should be approached with a similarly deliberate approach to, for example, avoid potentially performance-impairing mental fatigue (Weiler et al., 2024) during key periods. Therefore, when implementing more representative training, efforts should also be undertaken to understand how its integration influences the loads experienced by athletes. In non-aquatic sports, GPS systems and metrics derived from inertial measurement units could provide indications of external load during a drill or training session. Questionnaires like the NASA-TLX (Hart & Staveland, 1988), pre- and post-training mental and physical fatigue scales, as well as heart rate measures, could provide insight on internal load. Importantly, any measures used should have already been integrated for a period prior to a particular intervention: interpretation of values will be most meaningful if they can be compared to "regular" or pre-intervention training. Although many teams do have regular training monitoring questionnaires, such as session RPE after practices, or holistic wellness questionnaires, these may not offer precision about the physical and mental demands induced by a specific drill or session. Access to the latter is access to a source of feedback about whether the intended loads are being achieved in a given session, in addition to being a way to monitor load over time and adjust appropriately.

Self-reported perceptual measures may also be one way of assessing the effectiveness of an intervention. Indeed, in open skill sports like water polo that involve interaction with the opponent – and unlike sports in which performance is determined by a single metric – it can be more challenging to select which objective metrics should be used for quantifying "performance" improvements. For an initiative focused on enhancing representative training and exposing athletes to both the physical and mental demands of competitions, comparing players' responses to questionnaires like the NASA-TLX (Hart & Staveland, 1988) at competitions prior to and following the intervention could be of interest. Examples of results that could point in the direction of an effective intervention include scenarios where there are 1) equally high ratings of physical and mental demand for pre- and post-intervention competitions, but perceived performance is rated as higher for the post-intervention competition; 2) lower ratings of demand for the same perception of performance. These could also be coupled with an overall assessment of performance by the coach. That being said, given the sensitivity of performance to a plethora of different variables, qualitative tools for investigation may in fact be the most informative, since they can account for different contextual factors that may be difficult to capture with questionnaires or other quantitative measures. Accordingly, soliciting feedback from athletes and staff, in addition to observing attentively to capture less explicit cues, throughout the intervention will provide useful indications of adjustments that can be made to maximize overall impact. Then, after the intervention period, through both informal and structured settings, there would be high value in probing their perceptions of how effective the intervention was, as well as their reflections that could guide future initiatives.

As relevant as they are, research activities to support the eventual periodization and the assessment of effectiveness of a training intervention are constrained by time, financial, and expertise resources. These are barriers that also apply to the limitations and future directions of our other projects. In our investigation of the validity and reliability of a video-based test, a method in which reaction times could be extracted could provide further insight than accuracy results alone. While there are challenges in creating video-based tests with representative stimuli and responses for an aquatic sport, there is potential in the form of existing 360VR training methods for water polo goalkeepers (Richard et al., 2021). Quantifying the validity and reliability of this training could shed light on its applicability for talent identification and skill monitoring. When we investigated performance on cognitive tasks while simultaneously cycling, there were differences in performance and self-reported perceptual measures between the Stroop task and the water polo video-based task. It was uncertain if these results could be linked to the domain-specificity of the task or primarily to different cognitive functions solicited by the tasks. Designing studies with two tasks known to rely heavily on distinct cognitive functions and incorporating cerebral oxygenation measures via functional near-infrared spectroscopy are two ideas to begin addressing these types of questions. Brain imaging could also potentially provide mechanistic insight on the exercise intensity- and duration-related effects. Future studies that involve exercise conditions continued to exhaustion and time-series evaluation of simultaneous cognitive task performance would offer novel understanding on the temporal dynamics of cognitive functioning during exercise. In our study examining the hazard of decision-making errors, being able to include more games, as well as evaluations of defensive actions, in the analyses could lead to hazard functions that are more representative of teams' performance. Assessments of individual, rather than team, performance, using methods combining human and technological judgement, may also be intriguing. Finally, in the project to enhance representative training, implementing structured pressure training, in conjunction with the more physically- and cognitively- representative designs we created, would have been immensely valuable in targeting the emotional component of representativeness. When translating knowledge to action in high-performance sport, though, there are particular hurdles that even sufficient research resources cannot eliminate entirely. Namely, there is a complex social context that must be navigated. Solid relationships with those who have influence in the space (e.g., coaches, support staff) are a prerequisite, but their endorsement for the research-related activities is also essential.

Athletes may not understand the full importance of certain aspects of their participation, or simply may not care, which can lead to challenges in buy-in and adherence. With the level of trust and credibility that coaches and regular staff hold, their explicit support can make a significant difference in athletes' attitude and commitment (without removing the voluntary aspect of their participation). The same applies for gaining the buy-in of coaches and the power of having the support of staff for aspects related to their professional expertise. In general, devoting energy in strengthening the collaborative spirit with the decision makers and holders of power, including identifying mutually-agreed upon expectations and milestones, will only benefit the application of research to practice. Therefore, for research in this area to progress, there should be deliberate and thoughtful design of protocols, but our relationships with those in the environment – and the cultivation of their commitment and support – are equally important to the feasibility and quality of the activities that are pursued.

CONCLUSION

The work in this thesis was strongly shaped by questions surrounding match-play decision making that Water Polo Canada staff identified as opportunities for performance enhancement. In our research efforts to evaluate water polo-specific decision making, investigate cognitive performance during simultaneous physical exertion, map the existing literature on the effects of fatigue, and explore the evolution of decision-making performance during competition matches, we used novel approaches to further contribute to scientific knowledge. Our findings consistently supported the relevance of considering factors other than fatigue and of prioritizing representative designs. In parallel, as my role transitioned towards a more embedded one, it became clearer that we needed to confront the real-world complexities of high-performance sport training and competition preparation. These conclusions, along with the relationships fostered, paved the road for the most important – if we consider the original research aims - step of this thesis, in which we co-designed more representative training designs. Taken as a whole, this thesis depicts one example of integrated knowledge translation, in which the earlier work served to establish a solid foundation for both our understanding and our relationships with the athletes and staff, ultimately culminating in a collaborative process to harness research for action.

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