Ecological validity in exercise neuroscience research: A systematic investigation

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Abstract
The contribution of cortical processes to adaptive motor behaviour is of great interest in the field of exercise neuroscience. Next to established criteria of objectivity, reliability and validity, ecological validity refers to the concerns of whether measurements and behaviour in research settings are representative of the real world. Because exercise neuroscience investigations using mobile electroencephalography are oftentimes conducted in laboratory settings under controlled environments, methodological approaches may interfere with the idea of ecological validity. This review utilizes an original ecological validity tool to assess the degree of ecological validity in current exercise neuroscience research. A systematic literature search was conducted to identify articles investigating cortical dynamics during goal-directed sports movement. To assess ecological validity, five elements (environment, stimulus, response, body and mind) were assessed on a continuum of artificiality–naturality and simplicity–complexity. Forty-seven studies were included in the present review. Results indicate lowest average ratings for the element of environment. The elements stimulus, body and mind had mediocre ratings, and the element of response had the highest overall ratings. In terms of the type of sport, studies that assessed closed-skill indoor sports had the highest ratings, whereas closed-skill outdoor sports had the lowest overall rating. Our findings identify specific elements that are lacking in ecological validity and areas of improvement in current exercise neuroscience literature. Future studies may potentially increase ecological validity by moving from reductionist, artificial environments towards complex, natural environments and incorporating real-world sport elements such as adaptive responses and competition.

Abbreviations: CI, confidence interval; CS, closed-skill sports; ECOVAL, ecological validity assessment tool; EEG, electroencephalography; ERP, event-related potential; EV, ecological validity; ICC, interclass correlation coefficient; OS, open-skill sports; PSD, power spectral density analysis; VR, virtual reality.

Melissa Chang and Daniel Büchel share the first authorship of this article

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In many sports, exceptional physical abilities and cognitive skills are necessary for success (Tan et al., 2019). Processes within the human brain, even on a neuronal level (Maguire et al., 2000; Thaler et al., 2011), may therefore be a crucial determinant for performance and expertise. Exercise neuroscience is a new and emerging field that includes the measurement of brain activity during voluntary movement, whether the movement is simple or complex in specific sport contexts. The study of brain function in exercise neuroscience therefore provides valuable insights into the relationship between sports, brain and behaviour (Cheron et al., 2016; Park et al., 2015). Notably, differences in cortical activation and cortical event-related potentials (ERPs) demonstrated that experts show improved abilities in processing task-related stimuli, for instance, in golfing and rifle shooting (Babiloni et al., 2008; Baumeister et al., 2008; Deeny et al., 2003; Loze et al., 2001). These findings point to the contribution of cortical processes in sports performance, in which the coupling of sensory stimuli and motor behaviour plays a crucial role to adapt to interactive stimuli within the environment.

Especially during voluntary movement, complex neural processes underlie goal-directed behaviour initiated in response to specific external stimuli or by will (Deliagina et al., 2008). Because goal-directed movement induces cortical mechanisms like stimulus processing, anticipation and motor execution (Neuper & Pfurtscheller, 2001), subject–environment interaction appears to be more complex in goal-directed movement compared with locomotion or reflex-type motion. From an external stimulus perspective, one can further categorize voluntary movement into open-skill (OS) and closed-skill (CS) sports (Knapp, 1963). Whereas CS sports resemble sports targeted towards a stable and predictable stimulus (e.g. golfing towards a fix hole), OS sports resemble those activities targeted towards stimuli in unpredictable and ever-changing environments (e.g. reacting to a serve in table tennis) (Gu et al., 2019). Therefore, the study of cortical function during OS and CS sports offers valuable insights into cognitive processes and mental states associated with adaptive motor behaviour. Due to its advantages in mobility and measuring cortical dynamics at a high temporal resolution (Mehta & Parasuraman, 2013), researchers often utilize the electroencephalogram (EEG) to monitor cortical activity during movement. However, it is still unclear whether cortical mechanisms assessed from the EEG reflect the real-world affordances induced by adaptive behaviour. Because neuroimaging studies are frequently performed under highly controlled laboratory conditions (Ladouce et al., 2017), current evidence may display a limited representation of the complex individual–environment interaction. Especially for outdoor sports, environmental factors may have a huge effect on behaviour and neurophysiology, as embedding a task into a sensorial rich environment alters task affordances (Reiser et al., 2019). Reductionist approaches in the lab may therefore bias an individual’s interaction with the environment compared with the affordances in real-world sports.

The question of whether a study matches the complexity of real-world behaviour is resembled under the criteria of ecological validity (EV) (Ladouce et al., 2017). Although many have called for the importance of conducting ecologically valid studies, there exists no objective way to assess or quantify the EV of an experiment (Bronfenbrenner, 1977; Brunswik, 1943; Neisser, 1976; Schmuckler, 2001). In the past, EV has been defined as the extent to which the environment experienced by the subjects in a scientific investigation has the properties it is supposed or assumed to have by the experimenter (Bronfenbrenner, 1977), whereas more recently definitions refer to the extent to which the findings of a study accurately reflect real-world phenomena (Osborne-Crowley, 2020). To describe EV, various elements of the individual–environment interaction can be addressed, including not only the experimental environment, the stimulus or the response but also more abstract elements like the degrees of freedom of the body and mind (Chiel & Beer, 1997; Schmuckler, 2001). Consequently, research on the brain’s contribution to sports performance extends beyond mechanistic movement-related factors and includes elements such as the environment and the variability of task conditions.

Fortunately, the development of new technology such as the mobile EEG allows researchers to investigate brain activity during sports movement (Baumeister, 2013; Christie et al., 2019, 2020; Skrzeba & Vogt, 2018), which surpasses traditional limitations regarding device mobility (Mehta & Parasuraman, 2013) and artefacts caused during sports movement (Gwin et al., 2010; Ladouce et al., 2017). These developments further allow for EEG measurements during unconstrained sports movements in real-world environments, such as in golfing greens and shooting ranges (del Percio et al., 2011; Reinecke et al., 2011), and permit systematic investigations on how environmental factors affect movement coordination and its underlying brain activity. Nevertheless, the issue of EEG artefact contamination as a function of body movement remains problematic, especially when it comes to the analysis of cortical activity time-locked to movement. In this case, muscle activity and mechanical forces may overlap movement-related EEG outcomes in low and high frequency ranges and could lead to...
misinterpretations of neural signals (Castermans et al., 2014). Thus, an increase in the degrees of freedom of movement may favour non-brain contributions to the surface EEG signal. To solve this problem, complex analytical approaches are required to detangle brain and non-brain contributions to EEG signals. For instance, additional information from inertial motion units (Beach et al., 2021) or electromyography (Li et al., 2021) could help decompose movement-contaminated sections of EEG recordings during sports. Furthermore, technical solutions like dual-layer EEG set-ups (Nordin et al., 2019) may improve signal-to-noise ratio by removing signal components stemming from mechanical impacts on electrodes. As such, the incorporation of multimodal data streaming may prove beneficial in future EEG studies in face of detangling cortical and non-cortical contributions to scalp EEG during dynamic and acyclic exercise paradigms.

Because latter techniques require high methodological and technical efforts, EEG studies, especially in the last decade, tend to take on minimal behavioural approaches. For instance, the reduction of the degrees of freedom in movement serves as an attempt to minimize movement artefacts and to increase the internal validity of results (Ladouce et al., 2017; Makeig et al., 2009). Particularly, laboratory-based experiments restrict natural cognition by implementing artificial stimuli and simplified motor responses (Ladouce et al., 2017). This reductionist approach partly counteracts the nature of the study of sports, which often takes place in dynamic (outdoor) environments requiring a continuous adaptation of the individual from one situation to another (Gu et al., 2019). Therefore, it seems paramount for future research in adaptive sports behaviour to investigate how experimental settings are simplified and how these restrictions hypothetically affect outcomes in sports science research. Addressing adaptive behaviour in exercise neuroscience research therefore raises the question whether laboratory research paradigms are comparable with real-world behaviour (Bronfenbrenner, 1977; Osborne-Crowley, 2020). Although the minimalistic approaches might be effective in reducing data noise originating from non-brain sources, the reduced complexity of experimental set-ups may be biased against the neural processes underlying dynamic adaptive behaviour in sports. Furthermore, decisive factors such as flow and stress are important in sports performance under competitive conditions (Leroy & Cheron, 2020). Considering flow and stress as intra-individual degrees of freedom in the perception and processing of environmental information, reductionist experiments based on repetition and control over the experimental paradigm may not allow for changes of mind within a given task (Parada, 2018). Therefore, although limiting the participants’ behaviour may result in less noise in the EEG data, it may hinder the analysis of cortical correlates reflecting real-world brain mechanisms.

The objective of this review was to systematically assess the degree of EV in the current body of exercise neuroscience literature investigating goal-directed sports tasks. To this aim, the present study develops and utilizes an original EV assessment tool (ECOVAL) to evaluate the degree of EV in current literature. In order to apply the concept of EV, we define ‘EV’ as the extent to which experimental conditions accurately reflect sports participation in a real sports setting. This literature review attempts to objectively evaluate mobile EEG research and to systematically analyse the degree of EV in experiments. The findings will help to describe the current state of EV in exercise neuroscience studies and to bring to light future directions in the conduction of research in exercise neuroscience.

2 | MATERIALS AND METHODS

2.1 | EV assessment

ECOVAL is an original development designed in an attempt to objectively assess EV in sport and exercise science studies. Five elements were selected based on previous publications in neuroscientific disciplines: environment, stimulus, response, mind and body. These elements were incorporated according to Schmuckler’s three dimensions of EV (environment, stimulus and response) in combination with elements of adaptive behaviour (nervous system, body and environment) (Chiel & Beer, 1997; Schmuckler, 2001). Environment refers to the objective elements that make up the experimental setting the study is conducted in. Stimulus refers to the elements within the environment that the movement of interest is targeted towards. Response refers to the movement of interest elicited by the target stimuli in order to assess sports performance. Body refers to the physiological processes utilized to perform the movement of interest within the given experimental paradigm. Mind refers to the mental processes utilized to perform the movement of interest within the given experimental paradigm, focusing on the cognitive processes responsible for the perception and processing of task-relevant information.

ECOVAL assess each element as either artificial or natural, and as either simple or complex. According to Holleman et al. (2020), research contexts can be evaluated on a dichotomous scale of artificiality–naturality and simplicity–complexity. Laboratory conditions are
considered ‘artificial’ and ‘simple’, whereas real-world situations are considered ‘natural’ and ‘complex’ (Holleman et al., 2020). To simplify the rating process for this study, ECOVAL evaluates each element as either artificial or natural and as either simple or complex on a dichotomous scale. Artificial is defined as something specifically designed for research purposes, and natural is defined as the original target appearing in the real world, which is to be understood by research (Hoc, 2010). The simplicity–complexity scale accounts for the representation of all possible variations of each element within the study design compared to the real world. Because levels of simplicity or complexity are highly dependent on subjective interpretation (Holleman et al., 2020), pre-established close-ended questions (or ‘yes-no questions’) are used to conduct the ratings. An affirmative answer results in the element being deemed as ‘natural’ or ‘complex’ with a score of 1, whereas a negative answer results in the element being deemed as ‘artificial’ or ‘simple’ with a score of 0. Elements are rated 0 if no information was provided in the article. Figure 1 depicts an overview of scale criteria and corresponding questions. For the element ‘mind’, the definitions of complexity and naturalness were defined rather broadly due to ambiguous associations with the term. Because we investigated the studies from a mechanistic perspective, setups were considered artificial if subjects were in any way restricted with regard to the perception and processing of task-relevant information, for example, due to instructions. For distinction between complexity and simplicity, the element ‘mind’ was considered simplified if experimental tasks were an isolated, repeated variation of the normal task with limited information perception and processing compared with the real-world situation. When the experiment required additional cognitive elements in addition to the movement itself, for example, decision making or inhibition, it was considered complex.

Because the ‘real-world’ affordances of a task may change depending on the sport studied, assessment is based on the experimental paradigm described in the manuscript as it compares to the performance of the sport in the real world. Each element scores either 0 (artificial/simplified) or 1 (natural/complex) on each subscale; thus, scores range from 0 to 2 for each element, and the total score for each study ranges from 0 to 10 for a total of five elements assessed. For a more comprehensive description of results, total scores are categorized into three levels: Level 1 (scores 0–3) and low EV, Level 2 (scores 4–6) and mediocre EV and Level 3 (scores 7–10) and high EV. Laboratory-specific conditions that are considered ‘artificial’ and ‘simple’ yield low scores and are less ecologically valid. Alternatively, real-world situations that are considered ‘natural’ and ‘complex’ yield high scores and are therefore more ecologically valid. It needs to be mentioned that this review only aims to assess the experimental settings of EEG sports science studies with regard to the aspect of EV. Therefore, the experimental findings of a given study will not be considered for this literature review.

### 2.2 | Literature review

This systematic review utilized the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach (Liberati et al., 2009). The primary information sources included are (1) PubMed, (2) Web of Science and (3) ProQUEST. Database search included search terms found in article titles, abstracts and keywords. The search terms were selected based on commonly used keywords in the field of exercise neuroscience. Specific neurophysiological search terms included variations of the following: MoBI, electroencephalography, EEG and ERP (event-related potentials). EEG measurement outcome search terms include variations of the following: power, potential, alpha and theta. Sport search terms include sport and exercise. Excluded search terms related to disease include variations of the following: disability, disease, injury and concussion. For example, the search string utilized for the PubMed database is as follows: (((MoBI OR electroencephalography OR eeg OR erp OR mobile brain/body imaging OR fNIRs) AND (power OR potential OR alpha OR theta)) AND (sport OR exercise)) NOT (disability OR disorder OR disease OR impairment OR injury OR concussion OR imagery OR resting state OR drugs OR medication OR cardiovascular OR strength OR force training OR sleep OR emotion OR animal OR running OR cycling OR depression OR stroke OR epilepsy). Results from each database were added to Mendeley and checked for duplicates.

The inclusion and exclusion criteria determined prior to the literature search were based on the application of neuroimaging technology during goal-directed voluntary movement. Studies were included if they utilized neurophysiological techniques (EEG) to study human cortical activation during the participation of sports. The sport in question must be included in the Olympic list of sports and must be one where the subject initiates an adaptive motor response targeted towards stimuli within the environment. Only articles in English were considered. Literature was excluded from this review if they only included patients with a disability without a healthy control group, if participants were only engaged in sports aiming at cardiovascular load, strength and force training or if the task requires only a binary or qualitative
response. Studies that only investigated cortical outcomes before or after exercise and not during motor response were also excluded.

All primary studies resulting from the literature search were screened for relevance based on the PRISMA approach (Liberati et al., 2009). After agreeing on the studies to be included, three independent raters conducted the EV assessment rating for each article. A detailed literature search process is shown in Figure 2.

2.3 | Results generation

Ratings were conducted utilizing a shared online platform. All three raters (M.C., D.B., K.R.) evaluated the studies independently using a predefined spreadsheet, and the raters met to discuss any rating discrepancies greater than 2 in the overall score after rating completion. All discrepancies were resolved through discussion, and results were transferred to a master rating sheet for statistical analysis. As the final score, the average of three raters was
computed and rounded down to the next integer for each study. The mean ratings were generated for each study and for each element, as is the count of studies for each rating. The interclass correlation coefficient (ICC) based on absolute agreement was also generated to objectively assess inter-rater reliability. For a more differentiated analysis, the included studies were categorized into ‘outdoors’ and ‘indoors’ sports based on the sport environment and into ‘open-skill’ and ‘closed-skill’ depending on the stimulus type and the target movement.

3 | RESULTS

3.1 | Study selection and characteristics

Literature searches included a total of 2070 studies, with 1894 articles remaining after duplicate removal. After initial screening by title and excluding studies unrelated to sports, 900 studies remain. All studies were then screened by abstract based on the predetermined inclusion criteria, and 119 studies were included for further consideration. The full-text articles for each of the studies were reviewed, and a total of 39 studies were eligible for inclusion. An additional eight studies that met the criteria for inclusion were identified by cross-checking references of the located papers. A total of 47 studies were included in the final selection.

The 47 studies included span across three major categories: indoor CS, outdoor CS and indoor OS sports (Figure 3). Sports included within the category ‘indoor CS’ (n = 18) include shooting, which takes place majorly in indoor ranges in which the body remains static and response is initiated via minor limb movement. The category ‘outdoor CS’ (n = 23) consists of archery and golf. These sports are majorly conducted outdoors and require...
multi-limb movement, but only minor whole-body movements while remaining in a fixed standing position. Sports included within the category ‘indoor OS’ \((n = 6)\) include basketball, badminton, ice hockey and table tennis. These sports are played indoors and require not only whole-body movement but also adaptive responses depending on the changing environmental cues during the sport. For an overview of the included studies, please refer to Table 1. A visualization of included sports is provided in Figure 3. EEG outcomes analysed included power spectral density (PSD) analysis \((n = 31)\), ERPs \((n = 13)\) and connectivity analysis \((n = 3)\).

### 3.2 General ratings

The average score in the ECOVAL assessment averages \(6.04 \pm 1.53\) across three independent raters. Mean study ratings were similar across all three independent raters. Of the 47 studies, two studies received Level 1 scores between 0 and 3, 33 studies received Level 2 scores between 4 and 6, and 12 studies received Level 3 scores of greater than 7. Figure 4 depicts the distribution of study ratings for all three raters. An analysis of the inter-rater reliability for absolute agreement between three raters revealed an ICC of 0.77 (90% confidence interval [CI]: 0.66–0.85). The mean difference in overall rating per study between all three raters was 0.42.

Indoor CS sports had the highest average of \(6.70 \pm 1.40\), followed by shooting \((n = 18)\), archery \((n = 3)\), ice hockey \((n = 2)\), table tennis \((n = 2)\), badminton \((n = 1)\) and basketball \((n = 1)\). Indoor CS sports had the highest average of 6.70 ± 1.40, followed by shooting (n = 18), archery (n = 3), ice hockey (n = 2), table tennis (n = 2), badminton (n = 1) and basketball (n = 1).

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| Study                  | Sport            | Environment                                  | Stimulus                                                                 | Response  | Body                      |
|-----------------------|------------------|----------------------------------------------|---------------------------------------------------------------------------|-----------|---------------------------|
| Babiloni et al. (2008)| Golfing          | Golf putting in golf-green simulator         | - 3 different golf hole sizes distanced 2.1 m from participant            | 100 putts | None                      |
| Babiloni et al. (2011)| Golfing          | Golf putting in golf-green simulator         | - 3 different golf hole sizes distanced 2.1 m from participant            | 100 putts | None                      |
| Baumeister et al. (2008) | Golfing        | Golf putting in laboratory on carpet        | - Real size golf hole distanced 3 m from participant—9 \times 9 grid surrounding hole for score rating | 5 blocks of 4 min putting | None                      |
| Baumeister et al. (2010) | Golfing        | Real golf putting vs. on Wii               | - Standard hole distances 3 m from participant—field: circles around holes for score rating | 2 blocks of 3 min putting | None                      |
| Bertolli et al. (2016)| Shooting         | Air pistol shooting                          | - shooting target (diameter 6 cm) distanced 10 m from participant       | 120 pistol shots | None                      |
| Cheng et al. (2015)   | Golfing          | Golf putting in a lab                        | - 10.8-cm hole distanced individually far away from participant          | 40 putts  | None                      |
| Cheng et al. (2017)   | Pistol shooting  | Shooting in indoor shooting range            | - Shooting target conforming to competition standards                   | 40 pistol shots | ‘Keep body static and eyes open for at least 3 s before movement’ |
| Christie et al. (2019)| Ice hockey       | Ice hockey shooting on ice                  | - One of five target areas within hockey net                             | 50 ice hockey shots | ‘Relax for 5 s before they prepared for the signal, each trial was’ exactly 18 s |
| Christie et al. (2020)| Ice hockey       | Ice hockey shooting on ice                  | - One of five target areas within hockey net                             | 50 ice hockey shots | None                      |
| Chuang et al. (2013)  | Basketball       | Basketball free throws in laboratory        | - Basketball rim 3.05 m tall distanced 4.6 m from participant            | 50 free throw attempts | None                      |
| Cooke et al. (2014)   | Golfing          | Golf putting in a lab                        | - Two different hole sizes (novices = 10.8 cm, experts = 5.4 cm) distanced 2.4 m from participant | 120 putts | None                      |
| Cooke et al. (2015)   | Golfing          | Golf putting in a lab                        | - Two different hole sizes (novices = 10.8 cm, experts = 5.4 cm) distanced 2.4 m from participant | 120 putts | None                      |
| Crews and Landers (1993) | Golfing        | Golfing in lab                               | - Hole of indoor putting green                                          | 40 putts  | No information            |
| Deeny et al. (2003)   | Rifle shooting   | Rifle shooting in soundproof room            | - 10-mm-diameter target distanced 5 m away from participant             | 40 rifle shots | None                      |
| Study                     | Sport           | Environment                   | Stimulus                                                                 | Response  | Body                        |
|--------------------------|-----------------|-------------------------------|--------------------------------------------------------------------------|-----------|-----------------------------|
| del Percio et al. (2009) | Air pistol      | Shooting in lab               | - Shooting target with diameter of 6 cm distanced 10 m from participant   | 120 pistol shots | None                        |
| del Percio et al. (2011) | Pistol shooting | Pistol shooting in range      | - Shooting target (diameter 6 cm) distanced 10 m from participant         | 120 pistol shots | None                        |
| Di Fronso et al. (2016)  | Pistol shooting | Air pistol shooting           | - Shooting target (diameter 6 cm) distanced 10 m from participant         | 120 pistol shots | None                        |
| Doppelmayr et al. (2008) | Rifle shooting  | Shooting in lab               | - Shooting target with diameter of 30 cm distanced 50 m from participant  | 50–70 rifle shots | None                        |
| Dyke et al. (2014)       | Golfing         | Golf putting in a lab         | - 2 × 2 cm target cross distanced 2.5 m from participant                 | 25 putts  | None                        |
| Gallicchio et al. (2016) | Golfing         | Golf putting in a lab         | - Two different hole sizes (novices = 10.8 cm, experts = 5.4 cm) distanced 2.4 m from participant | 120 putts | None                        |
| Gallicchio et al. (2017) | Golfing         | Golfing indoors              | - 10.8 cm hole distanced 2.4 m from participant                          | 50 putts  | ‘Putt ball when tone was silent’ |
| Gallicchio and Ring (2019)| Golfing         | Golf putting indoor green     | - Adhesive 0.6-cm-diameter paper targets—stimulus box determines target   | 120 putts | None                        |
| Haufler et al. (2000)    | Shooting        | Shooting and non-shooting task in a sound-attenuated testing chamber     | - Shooting target distanced 4 m from participant                          | 40 pistol shots | None                        |
| Hillman et al. (2000)    | Rifle shooting  | Laser rifle shooting, in-door range in sound-attenuated room             | - Shooting target part of optical simulation system                       | 40 rifle shots | None                        |
| Hülsdünker et al. (2019) | Table tennis    | Visuomotor task and table tennis task in lab                             | - Table tennis ball played by a ball machine, experimental target       | 100 strokes | None                        |
| Hülsdünker et al. (2020) | Table tennis    | Visuomotor task and table tennis task in lab                             | - Table tennis ball played by a ball machine, experimental target       | 100 strokes | None                        |
| Hunt et al. (2013)       | Pistol shooting | Pistol shooting in range      | - Size adjusted target distanced 5 m from participant                    | 40 pistol shots | Left eye occluded          |
| Study                  | Sport      | Environment                                      | Stimulus                                                                                                   | Response                | Body                     |
|-----------------------|------------|--------------------------------------------------|------------------------------------------------------------------------------------------------------------|-------------------------|--------------------------|
| Janelle et al. (2000) | Rifle      | Simulated shooting in lab                        | - Modified shooting target (diameter = 10 mm) distanced 5 m from participant                              | 40 pistol shots         | None                     |
| Jaquess et al. (2020) | Golfing    | Golf putt in lab                                 | - Fabric circle with a diameter of 4 in.                                                                   | 40 putts                | None                     |
| Kao et al. (2013)     | Golfing    | Golf putting in a lab                             | - 10-cm golf hole—concentric rings around hole                                                             | 100 self-paced putts    | ‘Keep body static 3 s before putting’ |
| Kerick et al. (2004)  | Pistol     | Pistol shots in indoor shooting range             | - Shooting target distanced 10 m from participant                                                          | 40 pistol shots         | None                     |
| Konttinen et al. (1998)| Rifle      | Laser rifle shooting, indoor range               | - Shooting target distanced 18 m from participant                                                          | 200 rifle shots         | None                     |
| Konttinen et al. (1999)| Rifle      | Laser rifle shooting, indoor range               | - Shooting target distanced 18 m from participant                                                          | 200 rifle shots         | ‘Motionless shooting hold for 7–8 s before trigger pull’ |
| Konttinen et al. (2000)| Rifle      | Laser rifle shooting, indoor range               | - Shooting target distanced 18 m from participant                                                          | 200 rifle shots         | None                     |
| Landers et al. (1994) | Archery    | Archery in laboratory                             | - Shooting target (120-cm target face) distanced 10 cm from participant                                     | 16 arrow shots          | ‘Hold bow at least 3 s before release’ |
| Loze et al. (2001)    | Pistol     | Air-pistol shooting, indoor 10 m range           | - Shooting target distanced 10 m from participant                                                          | 60 pistol shots         | None                     |
| Luchsinger et al. (2016)| Rifle     | Shooting in indoor shooting range                | - No information provided                                                                                  | 200 pistol shots        | None                     |
| Mann et al. (2011)    | Golfing    | Golf putting on a putting platform               | - Real size golf hole—imposed grid for accuracy                                                             | 90 putts                | None                     |
| Muangjaroen and Wongsawat (2012)| Golfing | Golf putting in laboratory on carpet | - 10.8-cm golf holes distanced 2.5 m from participant                                                  | 50 putts                | None                     |
| Pereira et al. (2018) | Pistol     | Shooting in virtual reality indoor range         | - 17 × 17 cm target distanced 10 m from participant                                                        | 80 pistol shots         | ‘Aim at least 5 s before pulling trigger’ |
| Reinecke et al. (2011) | Golfing    | Golf putting in a lab vs. field condition         | - Real size golf hole—imposed grid for accuracy                                                             | 4 blocks of 2 min putting | ‘Relax face muscles’ |
| Ring et al. (2015)    | Golfing    | Golf putting in a lab                             | - 10.8-cm hole distanced 2.4 m from participant                                                            | 100 putts               | ‘Putt ball when tone was silent’ |
| Salazar et al. (1990) | Archery    | Archery shooting, gym                            | - Arrow target distanced 45 m from participant                                                              | 16 arrow shots          | None                     |
| Skrzeba and Vogt (2018)| Badminton | Badminton backhand serves in court               | - Marked court area within badminton court                                                                 | 60 backhand serves      | None                     |
**TABLE 1** (Continued)

| Study | Sport  | Environment                                      | Stimulus                                                                 | Response | Body                                               |
|-------|--------|--------------------------------------------------|--------------------------------------------------------------------------|----------|---------------------------------------------------|
| Vogt et al. (2017) | Archery | Archery shooting, no information on location     | - Standard target (diameter 40 cm, height 130 cm) distanced 15 m from participant | 40 shots | ‘Avoid blinking and facial and neck contractions during aiming period’ |
| Wang et al. (2019) | Golfing | Golf putt in lab                                 | - Target distanced in an individual way that only 50% putts were successful | 60 putts | None                                               |
| Wang et al. (2020) | Golfing | Golfing in lab                                   | - Target distanced in an individual way that only 50% putts were successful | 60 putts | None                                               |

**Note:** Columns of studies investigating open-skill sports are highlighted in dark grey ($n = 6$), those investigating closed-skill sports taking place outdoors in light grey ($n = 23$) and studies investigating closed-skill sports taking place indoors in white ($n = 18$).

**TABLE 1** (Continued)

| Study          | Mind | Rationale                        | EEG outcome | ECOVAL rating |
|----------------|------|----------------------------------|-------------|---------------|
| Babiloni et al. (2008) | n/a  | Successful vs. unsuccessful     | Power       | 4.33          |
| Babiloni et al. (2011) | n/a  | Successful vs. unsuccessful     | Power       | 5             |
| Baumeister et al. (2008) | n/a  | Expertise                       | Power       | 6             |
| Baumeister et al. (2010) | n/a  | Real vs. virtual               | Power       | 8.33          |
| Bertollo et al. (2016) | n/a  | Motor control                   | ERD/ERS     | 6.67          |
| Cheng et al. (2015)  | n/a  | Neurofeedback training          | Power       | 6             |
| Cheng et al. (2017)  | n/a  | Successful vs. unsuccessful     | Power, connectivity | 6              |
| Christie et al. (2019) | n/a  | Motor control                   | Power       | 6.67          |
| Christie et al. (2020) | n/a  | Neurofeedback training          | Power       | 7.33          |
| Chuang et al. (2013) | n/a  | Instruction to retain competition performance routine | Power       | 6.33          |
| Cooke et al. (2014) | n/a  | High/low pressure conditions with competition incorporation | Expertise | 5.33          |
| Cooke et al. (2015) | n/a  | Expertise                       | Power       | 4             |
| Crews and Landers (1993) | n/a  | Expertise                       | Power       | 3.67          |
| Deeny et al. (2003)  | n/a  | Expertise                       | Connectivity | 6             |
| del Percio et al. (2009) | n/a  | Expertise                       | ERD/ERS     | 7             |
| Study                          | Mind | Rationale         | EEG outcome                      | ECOVAL rating |
|-------------------------------|------|-------------------|----------------------------------|---------------|
| del Percio et al. (2011)      | n/a  | Expertise         | Connectivity                      | 8.67          |
| Di Fronso et al. (2016)       | n/a  | Motor control     | ERD/ERS                          | 7             |
| Doppelmayr et al. (2008)      | n/a  | Expertise         | Power                            | 5.67          |
| Dyke et al. (2014)            | n/a  | Successful vs. unsuccessful | Power, connectivity | 3             |
| Gallicchio et al. (2016)      | n/a  | Expertise         | Connectivity                      | 5.67          |
| Gallicchio et al. (2017)      | n/a  | Training intervention | Power, connectivity | 6.33          |
| Gallicchio and Ring (2019)    | n/a  | Expertise         | Power                            | 4.67          |
| Haufler et al. (2000)         | n/a  | Expertise         | Power                            | 5.33          |
| Hillman et al. (2000)         | n/a  | Inhibition        | Power                            | 5.33          |
| Hülsdünker et al. (2019)      | n/a  | Motor control     | Power                            | 4.33          |
| Hülsdünker et al. (2020)      | n/a  | Motor control     | ERP                              | 5             |
| Hunt et al. (2013)            | n/a  | Successful vs. unsuccessful | Power | 7             |
| Janelle et al. (2000)         | n/a  | Expertise         | Power                            | 5             |
| Jaquess et al. (2020)         | n/a  | Monetary reward   | Training intervention            | Power, connectivity | 6.67 |
| Kao et al. (2013)             | n/a  | Successful vs. unsuccessful | Power | 6             |
| Kerick et al. (2004)          | n/a  | Training intervention | ERP | 9             |
| Konttinen et al. (1998)       | n/a  | Expertise         | Brain slow potentials (ERP)       | 7.67          |
| Konttinen et al. (1999)       | n/a  | Expertise         | Brain slow potentials (ERP)       | 6             |
| Konttinen et al. (2000)       | n/a  | Expertise         | Electro cortical slow potentials (SPs), readiness potential (RPs) | 8.33          |
| Landers et al. (1994)         | n/a  | Successful vs. unsuccessful | ERP | 4.67          |
| Loæe et al. (2001)            | n/a  | Simulated competition environment | Successful vs. unsuccessful | Power | 9             |
| Luchsinger et al. (2016)      | n/a  | Expertise         | Power                            | 5.33          |
| Mann et al. (2011)            | n/a  | Expertise         | Bereitschaft potential (BP) ERP  | 5.33          |
| Muangjaroen and Wongsawat (2012) | n/a  | Successful vs. unsuccessful | Power | 4.67          |
3.3 | Environment

This element received an overall average rating of $0.55 \pm 0.45$, with an average score of $0.26 \pm 0.44$ for the artificiality–naturalness scale and an average score of $0.29 \pm 0.46$ on the simplicity–complexity scale. In terms of study location, the majority of the studies were conducted within the laboratory instead of the sports-specific real-world setting. For instance, many golfing studies were conducted indoors instead of on a golf course, and some shooting studies were conducted in the laboratory instead of a shooting range (Cooke et al., 2015; Hillman et al., 2000). On the other hand, a few studies have demonstrated the possibility of conducting measurements in the real-world sports environment, such as shooting studies being conducted in indoor shooting ranges and golfing studies being conducted successfully on the golf field (Hunt et al., 2013; Loze et al., 2001; Reinecke et al., 2011). These examples demonstrate the ability of current mobile neuroimaging techniques to conduct measurements within the real-world environment.

3.4 | Stimulus

The element ‘stimulus’ had an average overall score of $1.32 \pm 0.47$, with an average score of $0.63 \pm 0.48$ for the artificiality–naturalness scale and an average score of $0.69 \pm 0.46$ on the simplicity–complexity scale. Experiments generally utilized real-world sporting equipment, such as competition standard pistol shooting targets (del Percio et al., 2011; Kerick et al., 2004), international standard basketball equipment (Chuang et al., 2013) and standard golf holes (Mann et al., 2011; Wang et al., 2019, 2020). On the other hand, some studies utilized a modified version of the standard stimuli, such as golfing greens that include additional grid markings or scoring circles (Baumeister et al., 2008; Kao et al., 2013). These contributed to the complexity of the stimulus utilized, because although modified stimuli may not be considered ‘natural’ on the artificiality–naturalness scale, it is considered ‘complex’ due to additional contextual cues not present in the real world.

3.5 | Response

The element ‘response’ received an overall average score of $1.62 \pm 0.40$, with a score of $0.95 \pm 0.23$ on the artificiality–naturalness scale and a score of $0.67 \pm 0.47$ on the simplicity–complexity scale. Participants were mostly required to respond through actions relevant to the sport.
being studied, such as golfing studies requiring participants to putt golf balls and shooting studies asking participants to shoot at a target (Bertollo et al., 2016; Cheng et al., 2015). One observation is that although participants were performing real-world actions, they may be limited in the actions they perform. For example, various studies studying OS sports only required participants to perform a specific movement sequence like scoring a goal or serving a ball (Christie et al., 2019, 2020; Skrzeba & Vogt, 2018). In these studies, the experimental protocol only accounted for selected movement sequences that would be performed by an individual, instead of incorporating other possible gameplay scenarios such as passing the ball or maneuvering between opponents.

### 3.6 | Body

The element ‘response’ received an overall average score of $1.48 \pm 0.44$, with a score of $0.84 \pm 0.38$ on the artificiality–naturality scale and a score of $0.64 \pm 0.48$ on the simplicity–complexity scale. Due to technological limitations surrounding EEG measurement, participants were sometimes given instructions regarding their body movement, such as remaining still prior to executing the required action (Dyke et al., 2014; Kao et al., 2013) or to only perform a certain subset of a task like the backhand serve (Skrzeba & Vogt, 2018). Alternatively, various studies gave no limiting instructions, allowing participants to move freely and execute responses at will (Bertollo et al., 2016; Cheng et al., 2015). These experiments serve
as examples demonstrating the possibility to record brain activity while participants performed sport-specific tasks without motor limitations.

3.7 | Mind

The element ‘mind’ received an overall average score of 1.09 ± 0.50, with a score of 0.87 ± 0.35 on the artificiality–naturality scale and a score of 0.22 ± 0.42 on the simplicity–complexity scale. The high scores on the artificiality–naturality scale corroborated well with the observation that few, if any, participants were instructed on how or what to think, what to focus on, or given any direction regarding their cognitive processes such as attention and alertness. Alternatively, the element mind scored the lowest on the simplicity–complexity scale due to the fact that the majority (80%) of the studies did not incorporate elements beyond the movement itself, or any additional aspects that stimulate variations in the perception and processing of environmental information. On the other hand, studies that received the rating ‘complex’ included additional elements, such as stimulated competitive conditions, that may perturb additional cognitive processes such as inhibition and self-control on part of the participants (Cooke et al., 2014; Hunt et al., 2013; Kao et al., 2013).

4 | DISCUSSION

The aim of the present study was to assess the degree of EV in exercise neuroscience research. We found that the majority (70.2%) of the studies were mediocre in terms of having an ecologically valid experimental paradigm. Most importantly, the element ‘environment’ had the lowest overall rating, which points to a major area of improvement for future study designs. Additionally, it is important to note that although the element ‘response’ received the highest overall rating, it is not the highest rated element when considering only OS sports. When evaluating only OS sports, the element ‘body’ received the highest rating instead of ‘response’. These findings point towards a limited EV in current exercise neuroscience literature. Further details and particular observations will be discussed in subsequent paragraphs.

4.1 | Study representation and ratings

Characterized by high demands in adaptive behaviour and cortical processing, OS sports represent only 13% (6 studies) of the study selection and seem to be underrepresented in exercise neuroscience research. This correlates well with technological limitations surrounding neuroimaging. Traditional approaches and technological limits often require subjects to remain still and to attend to artificial stimuli while performing deliberately stereotyped responses (Ladouce et al., 2017), which limit the possibilities of conducting studies in ecologically valid environments and restrict study conduction to the laboratory. The development of techniques such as the mobile EEG allows researchers to first measure brain activity in relatively motionless sports such as shooting and golfing and then more recently OS sports such as basketball and ice hockey. This is in line with our study selection indicating a later start of adaptive sports research within the exercise neuroscience discipline (Chuang et al., 2013). With the continuous technological advances in the field of exercise science, we anticipate that future studies will continue to incorporate OS sports into this research domain while exploring new opportunities to improve the degree of EV in these set-ups.

Furthermore, we observe that indoor CS sports received, on average, the highest rating of the three categories. This is in line with our expectations, as sports included in this category (e.g. rifle shooting) are, for the most part, stationary and require a less complex individual–environment interaction. This reduces the need for movement and device mobility, thus bringing forth less concerns when replicating the environment and utilizing the standardized equipment during experimentation. These advantages, along with the ability to conduct studies in a real-world set-up (Loze et al., 2001), correlate with our observations of high EV scores for studies within this category.

Sports in the other two categories (outdoor CS sports and OS sports) often require major movement, in turn interfering with data recordings through movement artefacts. As such, researchers utilized reductionist approaches including the limitation of movement and reduction of specific aspects within the experimental set-up (Hunt et al., 2013; Kao et al., 2013). This causes elements considered in ECOVAL to move towards being ‘artificial’ and ‘simplified’, which contributes to the lower EV scores as observed in this study.

4.2 | Key Finding 1: Potential to conduct experiments in real-world ‘environment’

Across all 47 studies examined, the element ‘environment’ received the lowest average rating. This is primarily due to the fact that the majority of experimental procedures were conducted in a laboratory setting. For instance, both shooting and golfing studies were majorly
conducted in the laboratory instead of on the golf court or in a shooting range (Babiloni et al., 2008, 2011; Deeny et al., 2003). In these set-ups, the environment is not the natural real-world environment and often contains only relevant cues to conduct the given task, such as shooting in a soundproof room or putting with a golf simulator (Hillman et al., 2000; Mann et al., 2011). In the future, conducting studies in the real sports environment may provide more representative insights in the field of exercise neuroscience. This has already been proven possible in golfing and shooting studies (Kerrick et al., 2004; Reinecke et al., 2011) and can likely be applied to adaptive sport studies that require minimal environmental set-up such as table tennis. In this regard, advantages in device mobility and data processing tools seem to increase degrees of freedom without reducing the quality of assessed data (Wunderlich & Gramann, 2020). The concept of ‘affordances’ further suggests that the inherent ‘meaning’ of things perceived by an individual may shape the possibilities for potential actions and experiences (Gibson, 1979). Because this suggests that elements within the environment may limit or influence the functional capabilities of a particular individual, conducting studies in the real sports environment may be especially important as mobility and responses are of significant interest in sports & exercise science research (for more in-depth discussions, please see Heft, 2001). Furthermore, previous studies in the field of cognitive neuroscience indicated differences in collected data between laboratory and complex real-world environments. For instance, Protzak and Gramann (2018) found that ERPs differed between laboratory and real-world driving tasks and points towards caution when comparing EEG outcomes from real-world tasks and simulated environments. In line with that, Ladouce et al. (2019) observed modulations of ERPs when comparing treadmill walking with hallway walking, and Scanlon et al. (2020) reported modulations of ERPs in noisy compared with less noisy environments. Similar findings were observed by Reinecke et al. (2011), demonstrating a significant difference in frontal theta power when comparing laboratory and field golfing. Therefore, the amount of environmental information available during a given task may be directly related to mental processes like selective attention and distraction, which seem to dampen the degree of time-locked cortical activation in laboratory conditions (Ladouce et al., 2019). Further evidence identified EV as a contributing factor regarding the analysis of cortical correlates of human adaptive behaviour. For instance, Ko et al. (2016) reported significant increases in alpha and beta synchronization for realistic battlefield stimuli compared with geometric shape stimuli during a computerized stop signal task. Taken together, above-mentioned findings suggest that the complexity and summation of environmental cues can modulate brain dynamics and should be a point of consideration for future studies in adaptive behaviour. Especially for outdoor sports, the complexity of the environment may induce different neural processes than those experienced in controlled laboratory conditions (Reiser et al., 2019). Due to the majorly laboratory-based approach in current exercise neuroscience literature, current evidence might be biased due to reductionism in experimental procedures. Nevertheless, future studies are needed to further explore the effects of environmental complexity on brain-related outcomes in sports science research. This requires a systematic and controlled modulation of the environment from artificial set-ups towards naturalistic study designs, as proposed by Ladouce et al. (2019) in the context of reallocation of attention (Ladouce et al., 2019). In this regard, virtual reality (VR) technology may also provide a valuable opportunity to modify the environment of an athlete in a controlled manner. Although VR is receiving increased attention in the domains of exercise science (Düking et al., 2018; Vogt et al., 2019), it may also allow for systematic investigations in the field of EV, because it allows for a realistic replication of environments at different degrees of complexity (Peterson et al., 2018; Tremmel et al., 2019).

4.3 | Key Finding 2: An unhindered ‘body’ is required to perform an adaptive ‘response’ in OS sports

The elements ‘body’ and ‘response’ are influential over one another in sport and exercise science experimental paradigms, because one responds to an external stimulus via movement of the limbs, thus utilizing the ‘body’ to conduct the ‘response’. An interesting observation is that although the element ‘response’ received the highest average rating overall, the element ‘body’ received the highest average when considering only OS sports, indicating that responses may be less ecologically valid in OS sports experiment paradigms.

OS sports require that participants react to changing stimuli through the constant modification of their responses, and thus, their body. A key aspect in OS sports is the degree of freedom and the unpredictability of the sports situation (Di Russo et al., 2010). In our rating, we observe that although the element ‘response’ received the highest overall score, that is untrue when considering only OS sports. This may be due to experimental considerations of the analysed studies of OS sports only allowing for a limited degree of responses to increase the internal validity of study results (Ladouce et al., 2017).
Although OS sports such as table tennis and ice hockey require different movement techniques in response to varying stimuli, experimenters limited the investigation towards specific single-player movements. For instance, only utilizing backhand serves in a badminton study (Skrzeba & Vogt, 2018) or only investigating free throws in a basketball study (Cheng et al., 2015) served to control and further categorize movement responses to specific skills. Because reduced degrees of freedom are suggested to facilitate the interpretability and control within a given research paradigm, this measure counteracts EV (Parada, 2018). By limiting possibilities of responses, scores decrease in both the artificiality–naturality rating and the simplicity–complexity rating within the ‘response’ element. It remains speculative whether this limitation in the need for behavioural adaptation affects sports-related EEG outcomes. As suggested by Mierau et al. (2015), the degree of unpredictability of stimuli and associated motor responses may modulate, for instance, the activity in the prefrontal cortex.

Although technological advances in exercise science research provide full functionality and mobility for participants, we also observe a tendency of movement restriction in terms of experimental design. During sports participation, especially in OS sports, active behaviour is required and the basis for physical demands that require body, head and eye movements when users actively perceive information or respond to external stimuli (Doshi & Trivedi, 2009). Due to the active behaviour of participants during mobile recordings, data are often contaminated with activity stemming from non-brain sources, considered artefacts (Gramann et al., 2021). To combat this issue, researchers tend to restrict or limit the degree of movement responses to increase internal validity (Ladouce et al., 2017). Taking into account that a high degree of freedom, unpredictability and continuous action monitoring is a key element in OS sports (Di Russo et al., 2010), it can be inferred that movement restrictions in combination with repetitive study designs limit EV especially in OS sports investigations. As such, it is important to consider whether our attempts to measure cortical activity accurately and precisely has driven us towards a greater abstraction, isolation and focusing of measurements, inevitably contributing to an unintended reduction in EV (Ladouce et al., 2017). In addition to their beneficial effects in detecting movement-related artefacts, an implementation of additional information sources like motion sensors (Mustile et al., 2021) or eye tracking technology (Wunderlich & Gramann, 2020) in EEG research in sports and exercise may also allow for investigations of movement-associated brain activity in less restricted and therefore more variable and ecologically valid environments.

### 4.4 Additional findings: ‘Stimulus’ representation and the incorporation of competition to stimulate the ‘mind’

The element of ‘stimulus’ received the second highest average rating. This is supported by the majority of the studies utilizing real-world stimuli and standard sport equipment. Interestingly, simplified versions of the real-world stimulus are often observed in studies requiring repetitive performance, such as golf putts being performed from the same position towards the same goal over the same distance (Muangjaroen & Wongsawat, 2012; Ring et al., 2015). This repetitive nature is often observed in exercise neuroscience research, as current data processing requirements call for multiple measurements for a given analysis. However, recent data from Henz et al. (2018) reveal that repetitive performance of a given motor task under the same conditions may decrease activation within the frontal cortex at rest after exercise when compared with variable motor task conditions. With regard to the investigation of adaptive behaviour, we believe that repetitive experimental designs and stimuli may therefore bias functional outcomes in comparison with real-world neural mechanisms, which require subsequent motor adaptation and error processing, at least in some outdoor CS sports and OS sports. Along with the suggestions made in the discussion for the element ‘environment’, VR technology may provide an alternative way to maintain control while increasing the variability of stimuli in exercise neuroscience research. This technology has the potential to replicate additional elements present in the real-world environment and to create more challenging and variable stimuli under experimental constraints. Although this technology has been successfully applied in the context of dynamic postural control to increase cognitive load due to more challenging environments (Peterson & Ferris, 2019), additional experiments are needed to further explore the applicability and feasibility of VR technology.

Additionally, the range of stimuli presented in the analysed studies encompasses both sports-specific and artificial cues. Previous studies have demonstrated mediating effects of stimulus–response compatibility in baseball players (Nakamoto & Mori, 2008) and that stimulus specificity has implications in training agility and athletic performance (Young & Farrow, 2013). As stimulus artificiality may affect cortical processes and behavioural outcomes, these results point to the importance of utilizing sport-specific stimuli within the realm of exercise neuroscience research, which could be accomplished through the incorporation of real-world sport equipment and adherence to competition guidelines in the experimental set-up.
The element ‘mind’ had high scores on the artificiality–naturality scale, but low scores on the simplicity–complexity scale. Competition and distraction are important aspects in real-world sports present in most sport situations, and the low scores on the simplicity–complexity scale could be attributed to isolated performances of a given task in order to standardize experimental conditions. For instance, the majority of the studies (80%) did not include elements that are intended to perturb the mental processes, but of those that did, the measures utilized included playing against an opponent (Hunt et al., 2013; Pereira et al., 2018), perceived public ranking (Gallicchio et al., 2016; Loze et al., 2001) and monetary reward (Jaquess et al., 2020; Ring et al., 2015). Notably, previous studies have indicated differences in cortical activation and behavioural performance between non-competitive and competitive environments (Balconi & Vanutelli, 2018; Sinha et al., 2017). For instance, Zhang et al. (2021) found significant differences in temporal patterns of cortical activation during competitive versus non-competitive shooting exercises. In this regard, simplified experimental set-ups utilized in present sports science studies seem to under-represent the complexity of mental processes needed to perform in sports. To reach perfect EV with regard to the mental processes required to perform in sports, studies would need to assess brain activity under real competitive conditions.

Although this might work for individual CS sports activity such as tightrope walking (Leroy & Cheron, 2020), it may interfere with sports performance in OS sports due to movement restrictions. To combat this, a step towards a more ecologically valid experimental set-up may be the implementation of exercises including dual task (Moreira et al., 2021) or decision-making (Silva et al., 2020) elements that may serve as a well-controllable measure to increase the complexity of mental processes subserving motor skill performance. Furthermore, social interaction, expressed through various domains such as cooperation or competition, may possibly modulate cortical processes. Nevertheless, in-depth investigations of neural mechanisms contributing to cortical processing under cooperative or competitive conditions can be found elsewhere (Balconi & Vanutelli, 2016).

4.5 Methodological considerations

There are several limitations of our systematic search and review that warrant consideration. Firstly, we recognize that the questions and elements within ECOVAL were defined broadly, giving way to the possibility of subjective interpretation. To combat this, three independent raters were utilized during the scoring process to minimize personal bias and to account for variations in background and experience. Our assessment of inter-rater reliability thus revealed a reliable assessment of EV. Secondly, although the elements ‘body’ and ‘response’ are considered distinct elements within ECOVAL, we acknowledge that there may be interactive effects between these two items. The ‘body’ is the physical entity by means to execute the ‘response’, and in some cases, limitations on one may directly affect the other. Thirdly, we rated the elements as 0 when there was no information provided, which raises the possibility of differential ratings due to limitations surrounding publication requirements and varying interpretations regarding semantic usage. This was addressed through the use of three independent raters and through consulting provided images if available. Furthermore, this review did not analyse neuroscientific findings of individual studies, but instead focused on methodological approaches and experimental design. Doing so prevents the analysis of how the specific elements within the study may reduce the degree of EV and how that affects the outcomes provided by these studies. The effect of EV on brain outcomes therefore should be subject to future studies analysing brain function during sports (Reinecke et al., 2011). Respectively, as this review did not account for experimental aims, it is understood that although specific study protocols could have been conducted in an ecologically valid setting, some were pointedly conducted in the lab due to desired outcomes. Because training paradigms partly incorporate the usage of simplified motor tasks to improve motor learning outcomes (Capio et al., 2013), not all studies inherently aim to maximize EV. Lastly, we acknowledge that technological developments within the last two decades, regarding both EEG hardware and software, contribute to a limited comparability of studies published in the beginning of the century and recently published papers. However, we assume that an overall description of the EV of exercise neuroscience research will help to improve this aspect of EEG studies in future investigations.

5 | CONCLUSION

Our results indicate that the degree of EV in sport and exercise science research demonstrates room for improvement, specifically in terms of the environmental set-up. Instead of measuring brain activity during real-life performance of a given sport, actual sports science EEG studies tend to replicate the movement of interest under controlled and repetitive laboratory conditions. Future research efforts should address current gaps to minimize differences between laboratory and real-world set-up...
with aims to obtain ecologically valid measurements. The following challenges can be stated for upcoming studies:

i. Future studies investigating the effects of EV on sports-induced brain activity outcomes is required. In order to distinguish the contributions of each element towards the overall validity of experimental versus real-world settings, additional studies need to be conducted to better understand major influencing factors in the experimental set-up contributing to differences in cortical activity in sports science research.

ii. Exercise neuroscience studies should stimulate real-world sports settings and be conducted in the real sports environment to bridge the gap between artificial stimulations and real sports situations. Specific ways to implement this recommendation include designing experimental paradigms that stimulate a gamelike environment, incorporating real-life opponents and conducting measurements in the field. With the rise of mobile VR applications, realistic environments might be gradually adapted in a controlled manner to explore the effects of complex environments on brain processing.

iii. Experimental paradigms should refrain from utilizing elements that limit the degrees of freedom of the participants. These include instructions regarding participant response, technology that may limit participant mobility or limitations regarding the pace of experimental conduction. Although current sports science research paradigms have done well in retaining the authenticity of sport responses, there still exist limitations in movements and simplification of responses, especially in OS sports, which should be avoided in future investigations.

iv. Future studies may utilize the ECOVAL assessment tool to assess EV of published experimental studies in different fields of cognitive/neuroscience research. Therefore, slight adaptations of the specific questions might be necessary. Furthermore, the ECOVAL tool may be valuable as a self-assessment tool to account for EV when considering aspects of experimental set-up. Future studies may implement the ECOVAL questionnaire to evaluate study designs to assess whether it represents real-world demands of a sport.

These recommendations stem purely from an EV standpoint where we consider only specific elements within experimental paradigms in sport and exercise science. It is important to note that although investigations in the field of exercise neuroscience may benefit from conducting measurements in ecologically valid set-ups, it is crucial to first examine cortical activity in standardized laboratory conditions in order to establish feasibility and validity. Given that different disciplines may consider alternative approaches and aims, it remains important to conduct bidirectional research to maintain both internal and external validity (Ladouce et al., 2017) in order to disentangle the role of the brain in human sports performance.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

AUTHOR CONTRIBUTIONS

Substantial contributions to the conceptualization and design of the work were done by MC, DB, TL and JB. Study ratings were conducted by MC, DB and KR. The manuscript was written and revised by MC and DB with assistance from KR, TL and JB. All authors approved of the final version.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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REFERENCES

Babiloni, C., del Percio, C., Iacoboni, M., Infarinato, F., Lizio, R., Marzano, N., Crespi, G., Dassù, F., Pirritano, M., Gallamini, M., & Eusebi, F. (2008). Golf putt outcomes are predicted by sensorimotor cerebral EEG rhythms. The Journal of Physiology, 586, 131–139. https://doi.org/10.1113/jphysiol.2007.141630

Babiloni, C., Infarinato, F., Marzano, N., Iacoboni, M., Dassù, F., Soricelli, A., Rossini, P. M., Limatola, C., & del Percio, C. (2011). Intra-hemispheric functional coupling of alpha rhythms is related to golfer’s performance: A coherence EEG study. International Journal of Psychophysiology, 82, 260–268. https://doi.org/10.1016/j.ijpsycho.2011.09.008

Balconi, M., & Vanutelli, M. E. (2016). Competition in the brain. The contribution of EEG and fNIRS modulation and
personality effects in social ranking. *Frontiers in Psychology*, 7, 1587. https://doi.org/10.3389/fpsyg.2016.01587

Balconi, M., & Vanutelli, M. E. (2018). Functional EEG connectivity during competition. *BMC Neuroscience*, 19(19), 1–11. https://doi.org/10.1186/s12868-018-0464-6

Baumeister, J. (2013). Sensorimotor control and associated brain activity in sports medicine research. Paderborn Univ.

Baumeister, J., Reinecke, K., Cordes, M., Lerch, C., & Weiß, M. (2010). Brain activity in goal-directed movements in a real compared to a virtual environment using the Nintendo Wii. *Neuroscience Letters*, 481, 47–50. https://doi.org/10.1016/j.neulet.2010.06.051

Baumeister, J., Reinecke, K., Liesen, H., & Weiss, M. (2008). Cortical activity of skilled performance in a complex sports related motor task. *European Journal of Applied Physiology*, 104, 625–631. https://doi.org/10.1007/s00421-008-0811-x

Beach, C., Li, M., Balaban, E., & Casson, A. J. (2021). Motion artefact removal in electroencephalography and electrocardiography by using multichannel inertial measurement units and adaptive filtering. *Healthc. Technol. Lett.*, 8, 128–138. https://doi.org/10.1016/j.hilt.2016

Bertollo, M., Di Fronzo, S., Filho, E., Conforto, S., Schmid, M., Bortoli, L., Comani, S., & Robazza, C. (2016). Proficient brain for optimal performance: The MAP model perspective. *PeertJ*, 2016, e2082. https://doi.org/10.7717/peerj.2082

Bronfenbrenner, U. (1977). Toward an experimental ecology of human development. *The American Psychologist*, 32, 513–531. https://doi.org/10.1037/0003-066X.32.7.513

Brunswick, E. (1943). Organismic achievement and environmental variability. *Psychological Review*, 50, 255–272. https://doi.org/10.1037/h0060889

Capio, C. M., Poolton, J. M., Sit, C. H. P., Holmstrom, M., & Masters, R. S. W. (2013). Reducing errors benefits the field-based learning of a fundamental movement skill in children. *Scandinavian Journal of Medicine & Science in Sports*, 23, 181–188. https://doi.org/10.1111/j.1600-0838.2011.01368.x

Castermans, T., Duvinage, M., Cheron, G., & Dutoit, T. (2014). About the cortical origin of the low-delta and high-gamma rhythms observed in EEG signals during treadmill walking. *Neuroscience Letters*, 561, 166–170. https://doi.org/10.1016/j.neulet.2013.12.059

Cheng, M. Y., Huang, C. J., Chang, Y. K., Koester, D., Schack, T., & Hung, T. M. (2015). Sensorimotor rhythm neurofeedback enhances golf putting performance. *Journal of Sport & Exercise Psychology*, 37, 626–636. https://doi.org/10.1123/jsep.2015-0166

Cheng, M. Y., Wang, K. P., Hung, C. L., Tu, Y. L., Huang, C. J., Koester, D., Schack, T., & Hung, T. M. (2017). Higher power of sensorimotor rhythm is associated with better performance in skilled air-pistol shooters. *Psychology of Sport and Exercise*, 32, 47–53. https://doi.org/10.1016/j.psychsport.2017.05.007

Cheron, G., Petit, G., Cheron, J., Leroy, A., Cebolla, A., Cevallos, C., Petieau, M., Hoellinger, T., Zarka, D., Clarinval, A. M., & Dan, B. (2016). Brain oscillations in sport: Toward EEG biomarkers of performance. *Frontiers in Psychology*, 7, 246. https://doi.org/10.3389/fpsyg.2016.00246

Chiel, H. J., & Beer, R. D. (1997). The brain has a body: Adaptive behavior emerges from interactions of nervous system, body and environment. *Trends in Neurosciences*, 20, 553–557. https://doi.org/10.1016/S0166-2236(97)01149-1

Christie, S., Bertollo, M., & Werthner, P. (2020). The effect of an integrated neurofeedback and biofeedback training intervention on ice hockey shooting performance. *Journal of Sport & Exercise Psychology*, 42, 34–47. https://doi.org/10.1123/jsep.2018-0278

Christie, S., Werthner, P., & Bertollo, M. (2019). Exploration of event-related dynamics of brain oscillations in ice hockey shooting. *Sport Exercise and Performance Psychology*, 8, 38–52. https://doi.org/10.1037/spy0000134

Chuang, L. Y., Huang, C. J., & Hung, T. M. (2013). The differences in frontal midline theta power between successful and unsuccessful basketball free throws of elite basketball players. *International Journal of Psychophysiology*, 90, 321–328. https://doi.org/10.1016/j.ijpsycho.2013.10.002

Cooke, A., Gallicchio, G., Kavussanu, M., Willoughby, A., McIntyre, D., & Ring, C. (2015). Premovement high-alpha power is modulated by previous movement errors: Indirect evidence to endorse high-alpha power as a marker of resource allocation during motor programming. *Psychophysiology*, 52, 977–981. https://doi.org/10.1111/psyp.12414

Cooke, A., Kavussanu, M., Gallicchio, G., Willoughby, A., McIntyre, D., & Ring, C. (2014). Preparation for action: Psychophysiological activity preceding a motor skill as a function of expertise, performance outcome, and psychological pressure. *Psychophysiology*, 51, 374–384. https://doi.org/10.1111/psyp.12182

Crews, D., & Landers, D. (1993). Electroencephalographic measures of attentional patterns prior to the golf putt. *Medicine and Science in Sports and Exercise*, 25, 116–126. https://doi.org/10.1249/00005768-19930100-00016

Deeny, S. P., Hillman, C. H., Janelle, C. M., & Hatfield, B. D. (2003). Cortico-cortical communication and superior performance in skilled marksmen: An EEG coherence analysis. *Journal of Sport & Exercise Psychology*, 25, 188–204. https://doi.org/10.1123/jsep.25.2.188

del Percio, C., Babiloni, C., Bertollo, M., Marzano, N., Iacoboni, M., Infarinato, F., Lizio, R., Stocchi, M., Robazza, C., Cibelli, G., Comani, S., & Eusebi, F. (2009). Visuo-attentional and sensorimotor alpha rhythms are related to visuo-motor performance in athletes. *Human Brain Mapping*, 30, 3527–3540. https://doi.org/10.1002/hbm.20776

del Percio, C., Iacoboni, M., Lizio, R., Marzano, N., Infarinato, F., Vecchio, F., Bertollo, M., Robazza, C., Comani, S., Limatola, C., & Babiloni, C. (2011). Functional coupling of parietal alpha rhythms is enhanced in athletes before visuomotor performance: A coherence electroencephalographic study. *Neuroscience*, 175, 198–211. https://doi.org/10.1016/j.neuroscience.2010.11.031

Deliagina, T. G., Beloozerova, I. N., Zelenin, P. V., & Orlovsky, G. N. (2008). Spinal and supraspinal postural networks. *Brain Research Reviews*, 57, 212–221. https://doi.org/10.1016/j.brainresrev.2007.06.017

Di Fronzo, S., Robazza, C., Filho, E., Bortoli, L., Comani, S., & Bertollo, M. (2016). Neural markers of performance states in an Olympic athlete: An EEG case study in air-pistol shooting. *J. Sport. Sci. Med.*, 15, 214–222.
Konttinen, N., Lyttinen, H., & Viitasalo, J. (1998). Rifle-balancing in precision shooting: Behavioral aspects and psychophysiological implication. *Scand. J. Med. Sci. Sport.*, 8, 78–83. https://doi.org/10.1080/16000838.1998.tb00172.x

Ladouce, S., Donaldson, D. I., Dudchenko, P. A., & Ietswaart, M. (2017). Understanding minds in real-world environments: Toward a Mobile cognition approach. *Frontiers in Human Neuroscience*, 10, 694. https://doi.org/10.3389/fnhum.2016.00694

Landers, D., Han, M., Salazar, W., & Petruzzello, S. J. (1994). Effects of learning on electroencephalographic and electrocardiographic patterns in novice archers. *PsycNET*. https://psycnet.apa.org/record/1995-28334-001

Leroy, A., & Cheron, G. (2020). EEG dynamics and neural generators of psychological flow during one tightrope performance. *Scientific Reports*, 10, 1–13. https://doi.org/10.1038/s41598-020-69448-3

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gotzsche, P. C., Ioannidis, J. P. A., Clarke, M., Devereaux, P. J., Kleijnen, J., & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: Explanation and elaboration. *BMJ*, 339, b2700. https://doi.org/10.1136/bmj.b2700

Loze, G. M., Collins, D., & Holmes, P. S. (2001). Pre-shot EEG alpha-power reactivity during expert air-pistol shooting: A comparison of best and worst shots. *Journal of Sports Sciences*, 19, 727–733. https://doi.org/10.1080/026404101152475856

Luchsiner, H., Sandbakk, Ø., Schubert, M., Ettema, G., & Baumeister, J. (2016). A comparison of frontotemporal theta activity during shooting among biathletes and cross-country skiers before and after vigorous exercise. *PLoS ONE*, 11, e0150461. https://doi.org/10.1371/journal.pone.0150461

Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S. J., & Frith, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *Proceedings of the National Academy of Sciences*, 97, 4398–4403. https://doi.org/10.1073/pnas.070039597

Makeig, S., Gramann, K., Jung, T. P., Sejnowski, T. J., & Poizner, H. (2009). Linking brain, mind and behavior. *International Journal of Psychophysiology*, 73, 95–100. https://doi.org/10.1016/j.ijpsycho.2008.11.008

Mann, D. T. Y., Coombes, S. A., Mousseau, M. B., & Janelle, C. M. (2011). Quiet eye and the Bereitschaftspotential: Visuomotor mechanisms of expert motor performance. *Cognitive Processing*, 12, 223–234. https://doi.org/10.1007/s10339-011-0398-8

Mehta, R. K., & Parasuraman, R. (2013). Neuroergonomics: A review of applications to physical and cognitive work. *Frontiers in Human Neuroscience*, 7, 889. https://doi.org/10.3389/fnhum.2013.00889

Miera, A., Hülsländer, T., & Strüder, H. K. (2015). Changes in cortical activity associated with adaptive behavior during repeated balance perturbation of unpredictable timing. *Frontiers in Behavioral Neuroscience*, 9, 272. https://doi.org/10.3389/fnbeh.2015.00272

Moreira, P. E. D., de Oliveira Dieguez, G. T., da Glória Teles Bredt, S., & Praça, G. M. (2021). The acute and chronic effects of dual-task on the motor and cognitive performances in athletes: A systematic review. *International Journal of Environmental Research and Public Health*, 18, 1–13. https://doi.org/10.3390/ijerph18041732

Muangjaroen, P., & Wongsawat, Y. (2012). Real-time index for predicting successful golf putting motion using multichannel EEG. In Proceedings of the International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS, pp. 4796–4799. https://doi.org/10.1109/EMBC.2012.6347039

Mustile, M., Kourtis, D., Ladouce, S., Learmonth, G., Edwards, M. G., Donaldson, D. I., & Ietswaart, M. (2021). Mobile EEG reveals functionally dissociable dynamic processes supporting real-world ambulatory obstacle avoidance: Evidence for early proactive control. *The European Journal of Neuroscience*, 54, 8106–8119. https://doi.org/10.1111/ejn.15120

Nakamoto, H., & Mori, S. (2008). Effects of stimulus–response compatibility in mediating expert performance in baseball players. *Brain Research*, 1189, 179–188. https://doi.org/10.1016/j.brainres.2007.10.096

Neisser, U. (1976). *Cognition and reality: Principles and implications of cognitive psychology*. W.H. Freeman.

Neuper, C., & Pfurtscheller, G. (2001). Event-related dynamics of cortical rhythms: Frequency-specific features and functional correlates. *International Journal of Psychophysiology*, 43, 41–58. https://doi.org/10.1016/S0167-8760(01)00178-7

Nordin, A. D., Hairston, W. D., & Ferris, D. P. (2019). Human electrocortical dynamics while stepping over obstacles. *Scientific Reports*, 9, 1–12. https://doi.org/10.1038/s41598-019-41131-2

Osborne-Crowley, K. (2020). Social cognition in the real world: Connecting the study of social cognition with social reality. *Review of General Psychology*, 24, 144–158. https://doi.org/10.1037/0168-9925.2020.006483

Parada, F. J. (2018). Understanding natural cognition in everyday settings: 3 pressing challenges. *Frontiers in Human Neuroscience*, 12, 386. https://doi.org/10.3389/fnhum.2018.00386

Park, J. L., Fairweather, M. M., & Donaldson, D. I. (2015). Making the case for mobile cognition: EEG and sports performance. *Neuroscience and Biobehavioral Reviews*, 52, 117–130. https://doi.org/10.1016/j.neubiorev.2015.02.014

Pereira M., Argelaguet F., Millan J. d. R., & Lécuyer A. (2018). Novice Shooters With Lower Pre-shooting Alpha Power Have Better Performance During Competition in a Virtual Reality Scenario. *Frontiers in Psychology*, 9(527). https://doi.org/10.3389/fpsyg.2018.00527
Peterson, S. M., & Ferris, D. P. (2019). Group-level cortical and muscular connectivity during perturbations to walking and standing balance. *NeuroImage*, 198, 93–103. https://doi.org/10.1016/j.neuroimage.2019.05.038

Peterson, S. M., Furuichi, E., & Ferris, D. P. (2018). Effects of virtual reality high heights exposure during beam-walking on physiological stress and cognitive loading. *PLoS ONE*, 13, 1–17. https://doi.org/10.1371/journal.pone.0200306

Protzak, J., & Gramann, K. (2018). Investigating established EEG parameter during real-world driving. *Frontiers in Psychology*, 9, 2289. https://doi.org/10.3389/fpsyg.2018.02289

Reinecke, K., Cordes, M., Lerch, C., Koutsandréou, F., Schubert, M., Weiss, M., & Baumeister, J. (2011). From lab to field conditions: A pilot study on EEG methodology in applied sports sciences. *Applied Psychophysiology and Biofeedback*, 36, 265–271. https://doi.org/10.1007/s10484-011-9166-x

Reiser, J. E., Wascher, E., & Arnau, S. (2019). Recording mobile EEG in an outdoor environment reveals cognitive-motor interference dependent on movement complexity. *Sci. Reports*, 9(19), 1–14.

Ring, C., Cooke, A., Kavussanu, M., McIntyre, D., & Masters, R. (2015). Investigating the efficacy of neurofeedback training for expediting expertise and excellence in sport. *Psychology of Sport and Exercise*, 16, 118–127. https://doi.org/10.1016/j.psychsport.2014.08.005

Salazar, W., Landers, D. M., Petruzzello, S. J., Han, M., Crews, D. J., & Kubitz, K. A. (1990). Hemispheric asymmetry, cardiac response, and performance in elite archers. *Research Quarterly for Exercise and Sport*, 61, 351–359. https://doi.org/10.1080/02701367.1990.10607499

Scanlon, J. E. M., Redman, E. X., Kuziek, J. W. P., & Mathewson, K. E. (2020). A ride in the park: Cycling in different outdoor environments modulates the auditory evoked potentials. *International Journal of Psychophysiology*, 151, 59–69. https://doi.org/10.1016/j.ijpsycho.2020.02.016

Schmuckler, M. A. (2001). What is ecological validity? A dimensional analysis. *Infancy*, 2, 419–436. https://doi.org/10.1207/S15327078IN0204_02

Silva, A. F., Conte, D., & Clemente, F. M. (2020). Decision-making in youth team-sports players: A systematic review. *International Journal of Environmental Research and Public Health*, 17, 1–23. https://doi.org/10.3390/ijerph17113803

Sinha, N., Maszczyk, T., Zhang, W., Tan, J., & Dauwels, J. (2017). EEG hyperscanning study of inter-brain synchrony during cooperative and competitive interaction. 2016 IEEE Int. Conf. Syst. Man, Cybern. SMC 2016 - Conf. Proc., pp. 4813–4818. https://doi.org/10.1109/SMC.2016.7844990

Skrzeba, C., & Vogt, T. (2018). A cross-educational approach on skill-related movement technique performance: Central neuronal motor behaviour preceding the short badminton backhand serve. *Neuroscience Letters*, 686, 155–160. https://doi.org/10.1016/j.neulet.2018.09.005

Tan, S. J., Kerr, G., Sullivan, J. P., & Peake, J. M. (2019). A brief review of the application of Neuroergonomics in skilled cognition during expert sports performance. *Frontiers in Human Neuroscience*, 13, 278. https://doi.org/10.3389/fnhum.2019.00278

Thaler, L., Arnott, S. R., & Goodale, M. A. (2011). Neural correlates of natural human echolocation in early and late blind echolocation experts. *PLoS ONE*, 6, e20162. https://doi.org/10.1371/journal.pone.0020162

Tremmel, C., Herff, C., Sato, T., Rechowicz, K., Yamani, Y., & Krusienski, D. J. (2019). Estimating cognitive workload in an interactive virtual reality environment using EEG. *Frontiers in Human Neuroscience*, 13, 1–12. https://doi.org/10.3389/fnhum.2019.00401

Vogt, S., Skjærøe-Maroni, N., Neuhaus, D., & Baumeister, J. (2019). Virtual reality interventions for balance prevention and rehabilitation after musculoskeletal lower limb impairments in young up to middle-aged adults: A comprehensive review on used technology, balance outcome measures and observed effects. *International Journal of Medical Informatics*, 126, 46–58. https://doi.org/10.1016/j.ijmedinf.2019.03.009

Vogt, T., Kato, K., Schneider, S., Türk, S., & Kanosue, K. (2017). Central neuronal motor behaviour in skilled and less skilled novices – Approaching sports-specific movement techniques. *Human Movement Science*, 52, 151–159. https://doi.org/10.1016/j.humov.2017.02.003

Wang, K. P., Cheng, M. Y., Chen, T. T., Chang, Y. K., Huang, C. J., Feng, J., Hung, T. M., & Ren, J. (2019). Experts’ successful psychomotor performance was characterized by effective switch of motor and attentional control. *Psychology of Sport and Exercise*, 43, 374–379. https://doi.org/10.1016/j.psychsport.2019.04.006

Wang, K. P., Cheng, M. Y., Chen, T. T., Huang, C. J., Schack, T., & Hung, T. M. (2020). Elite golfers are characterized by psychomotor refinement in cognitive-motor processes. *Psychology of Sport and Exercise*, 50, 101739. https://doi.org/10.1016/j.psychsport.2020.101739

Wunderlich, A., & Gramann, K. (2020). Eye movement-related brain potentials during assisted navigation in real-world environments. *The European Journal of Neuroscience*, 54, 8336–8354.

Young, W., & Farrow, D. (2013). The importance of a sport-specific stimulus for training agility. *Strength Cond. J.*, 35, 39–43. https://doi.org/10.1519/SSC.0b013e31828b6654

Zhang, J., Shi, Y., Wang, C., Cao, C., Zhang, C., Ji, L., Cheng, J., & Wu, F. (2021). Freshening electroencephalographic activity of professional shooters in a competitive state. *Computational Intelligence and Neuroscience*, 2021, 1–9. https://doi.org/10.1155/2021/6639865

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