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Review

Making the case for mobile cognition: EEG and sports performance

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ABSTRACT

In the high stakes world of International sport even the smallest change in performance can make the difference between success and failure, leading sports professionals to become increasingly interested in the potential benefits of neuroimaging. Here we describe evidence from EEG studies that either identify neural signals associated with expertise in sport, or employ neurofeedback to improve performance. Evidence for the validity of neurofeedback as a technique for enhancing sports performance remains limited. By contrast, progress in characterizing the neural correlates of sporting behavior is clear: frequency domain studies link expert performance to changes in alpha rhythms, whilst time-domain studies link expertise in response evaluation and motor output with modulations of P300 effects and readiness potentials. Despite early promise, however, findings have had relatively little impact for sports professionals, at least in part because there has been a mismatch between lab tasks and real sporting activity. After selectively reviewing existing findings and outlining limitations, we highlight developments in mobile EEG technology that offer new opportunities for sports neuroscience.

Contents

1. Introduction

Elite sports competitions are major social and cultural events and the constant pressure to improve results has turned the investigation of sports performance into big business. Athletes are now supported by a range of specialist coaches and trainers, all aiming to stimulate changes in performance that can make the difference between winning and losing. Consequently, sports professionals have become interested in brain imaging, both as a route to a better understanding of the basic mechanisms underlying sporting behavior, and as a means to develop new methods to enhance performance. Equally, cognitive neuroscientists have

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become increasingly interested in sporting behavior, at least in part because elite sport provides an ideal model for understanding expertise – both in its acquisition and execution. In practice, however, reflection on what is required to be successful at the highest level in sport reveals a multifaceted picture of optimal performance. As well as possessing physical prowess, elite athletes must develop a range of sport specific cognitive skills and exhibit superior integration across the domains of perception, cognition and action (Yarrow et al., 2009). In this context, the emerging field of sports neuroscience seeks to produce greater understanding of brain-behavior links, ultimately aiming to inform sporting practice and enhance performance.

Cognitive neuroscience employs a range of brain imaging methods to investigate links between brain and behavior, but many are simply impractical for studying sporting behavior, particularly outside of the laboratory (e.g., functional Magnetic Resonance Imaging, single cell electrophysiology and Magneto-encephalography). By contrast, techniques that allow brain stimulation (e.g., Transcranial Magnetic Stimulation) offer genuine potential to enhance real-world sports performance (for a review see Yarrow et al., 2009). Although brain stimulation techniques can be used to directly induce changes in brain function independent of agency, the long-term consequences of brain stimulation remain unknown (Davis and Van Koningsbruggen, 2013). Moreover, in competitive contexts, the use of brain stimulation techniques raises serious ethical issues that have yet to be fully addressed by sports practitioners (Banissy and Muggleton, 2013; see Davis, 2013, for discussion of 'neurodoping'). Fortunately, however, one brain imaging methodology avoids the practical and ethical concerns discussed above, namely EEG (the Electroencephalogram).

EEG is one of the oldest methods for assessing the relationship between brain and behavior, and provides a direct real-time measure of neural activity. EEG is recorded using electrodes placed at specific locations across the scalp (e.g., frontal, temporal, parietal, occipital etc.); hence it is relatively inexpensive and easy to apply (see Fig. 1 for a schematic recording set up). Importantly, although EEG provides limited spatial resolution about the origins of neural activity, it has exceedingly high temporal resolution – making it ideal for tracking the rapid execution of sensory, cognitive and motor processes inherent to sporting behavior. Indeed, from a historical perspective, researchers have long appreciated that EEG methods are highly suited to identifying the neural mechanisms critical for sports performance (e.g., Crews and Landers, 1993; Hatfield et al., 1984; Salazar et al., 1990). Similarly, EEG has long been used to influence behavior, via neurofeedback training, which facilitates recognition and modification of mental states associated with particular patterns of cortical arousal and concomitant behavioral outcomes (e.g., Kamiya, 1962, 1968; Lubar and Shouse, 1976; Landers et al., 1991).

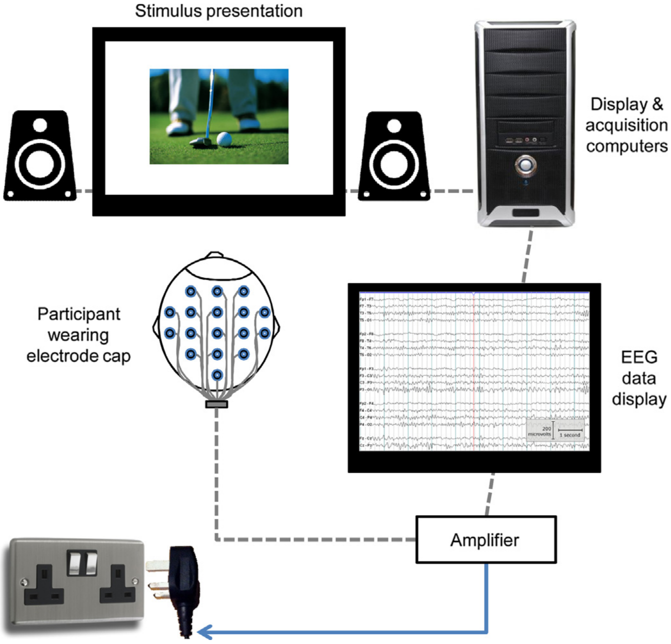

Fig. 1. Standard fixed position laboratory set up for recording EEG, showing equipment connections. Dashed lines indicate wired connections between pieces of equipment and the solid line illustrates the connection to the power supply.

Here we provide a selective overview of evidence to date, derived from studies investigating a range of sporting behavior, including the use of EEG as a neurofeedback technique. As we show, the evidence base at this stage remains limited, and we highlight methodological, terminological and analytic concerns. Moreover, for the most part, existing studies largely reflect laboratory-based investigations, with only a small number employing EEG during real-world sporting behavior. As a result, current findings fail to capture the complexity of the neural mechanisms implicated in active sports performance. Critically, however, as we highlight toward the end of the review, recent developments in mobile EEG technology provide an unprecedented opportunity to circumvent many of the issues inherent in existing work. Moving out of the lab and into the world will undoubtedly create new challenges that must be addressed, but the application of mobile EEG for assessing sports performance clearly has the potential to revolutionize the neuroscience of sporting behavior.

2. EEG in the frequency domain: alpha activity and neural efficiency

EEG research within the sporting context has largely focused on alpha rhythms (8–12 Hz). Alpha rhythms are clearly visible in raw EEG as a distinct set of deflections (oscillations) in the ongoing brainwaves; importantly alpha is easily distinguished from other rhythms (e.g., Theta at 4–7 Hz, and Beta at 15–30 Hz). Alpha is the most dominant frequency in the EEG of adults and has also been the most extensively studied in the wider literature (for a review see Başar, 2012). Historically, no clear agreement has been reached regarding the functional meaning of EEG alpha wave activity or even which measures best characterize it. The physiological basis of alpha signals (including anatomical and topographical factors) means that measurement of alpha activity can involve tracking changes in the amplitude, frequency or phase of underlying oscillations. As a result, reported indices of alpha may, for example, reflect changes in individual spectral alpha peak frequency, or changes in power within an individually determined alpha range (for detailed discussion see Bazanova and Vernon, 2013). Given advances in the measurement of alpha, it is perhaps unsurprising that since the original discovery of alpha rhythms by Hans Berger (1929), claims regarding the functional role of alpha oscillations have changed substantially. While early work associated alpha with cortical idling or disengagement from cognitive processing (e.g., see Adrian and Matthews, 1934), a wealth of contemporary research now supports the view that alpha plays an active role in cognitive processing (e.g., see Cooper et al., 2003; Klimesch et al., 2007).

Today it is generally agreed that alpha oscillations operate to actively inhibit unnecessary or conflicting processing in the cortex, and are often described as a mechanism for increasing signal-to-noise ratios or controlling task irrelevant processing (Klimesch et al., 2000; Pfurtscheller and Lopes da Silva, 1999). Consequently, alpha activity can be detected at multiple locations across the scalp, in response to a wide array of task demands; from this perspective alpha reflects a change in processing that can be observed for a range of different functions. Support for this view comes from findings showing that distinct sub-bands of alpha are associated with multiple operations, many of which are highly relevant to sport, including global arousal and attentional processes (Klimesch, 1999; Pfurtscheller and Lopes da Silva, 1999; Thut et al., 2006), elaboration of sensorimotor or semantic information (Klimesch et al., 1996, 1997, 1998; Klimesch, 1999), maintenance in working memory (Jensen and Tesche, 2002; Tuladhar et al., 2007), volitional inhibition of motor programmes (Hummel et al., 2002), and motor learning (Jancke et al., 2006; Koeneke et al., 2006). Before providing further details of the evidence relating to sport, we first introduce key terminology employed within the EEG literature. We will then summarize EEG research findings and related methodologies that have measured cognitive and motor skill behaviors and can be interpreted within theoretical models of expertise and skill acquisition.

Analytically, levels of alpha in the sports literature are typically characterized by decomposing the raw EEG signal into constituent frequency components using the Fourier transform to provide a “power spectrum” (see Fig. 2). In essence, spectral power reflects the square of the average peak-to-peak magnitude over a specified time period or epoch. Increases or decreases in spectral power in specific frequency bands are established relative to a predefined baseline. For example, resting state alpha (e.g., recorded eyes-closed, while inactive) is often used to provide a baseline from which changes in alpha power can be measured (e.g., eyes-open, during task performance). Because alpha is always present in raw EEG to some degree, the choice of baseline has significant impact on the pattern of brain activity reported. Changes in power also have specific terms within the EEG literature: Event-Related Desynchronization (ERD) is used to refer to a reduction in spectral power relative to baseline, while Event-Related Synchronization (ERS) describes an increase in spectral power relative to baseline (Pfurtscheller, 1992). Functionally, alpha ERD is described as reflecting the release of cortical inhibition, while alpha ERS signals the presence of inhibition. The concepts of inhibition and neural efficiency are pervasive in the sports EEG literature, and are consistent with several models of skill learning that have been highly influential in the field of sports science.

In a seminal theoretical paper, Fitts and Posner (1967) identified three distinct stages of skill acquisition (an early cognitive stage, an intermediate associative stage and a final autonomous stage) that reflect increasing efficiency of execution. The initial cognitive stage is characterized by effortful processing, supporting the conscious regulation of movement. The second associative stage is characterized by more efficient processing of task relevant sensory information and greater efficiency in the execution of movement, while the final autonomous stage captures the transfer from conscious regulation of movement to automaticity. Whilst Fitts and Posner offer a specifically cognitive account of expertise, alternative physiological models also exist within the sports literature. For example, expertise related changes in movement efficiency (i.e., when coordinating and controlling joints and muscle function in motor skills) have been explored and evaluated relative to Bernstein’s notion of ‘freezing’ and ‘degrees of freedom’ in movement (Bernstein, 1967).

From a physiological perspective, expertise requires efficiency in motor output programming. Initially inefficient movement solutions display a fixing (freezing) of joints and an increased activation of muscle groups relative to task requirements. With practice and time the restriction in degrees of freedom develops, resulting in a greater efficiency in movement, accomplished by a release of joint restrictions and superior muscle functioning (e.g., Anderson and Sidaway, 1994; Sparrow, 1992). Furthermore, with relevant experience and exposure, expertise results in coordination and control, allowing resistance to develop against intervening factors such as anxiety and competition pressure (Collins et al., 2001). This ability to self-regulate cognition, emotion and movement behavior is relevant to successful sports performance and appears important for an effective transition to the automatic level of performance (Singer, 2002). In summary, theoretical models of motor learning and skill acquisition help examine expertise with reference to both cognitive and physiological levels of explanation.

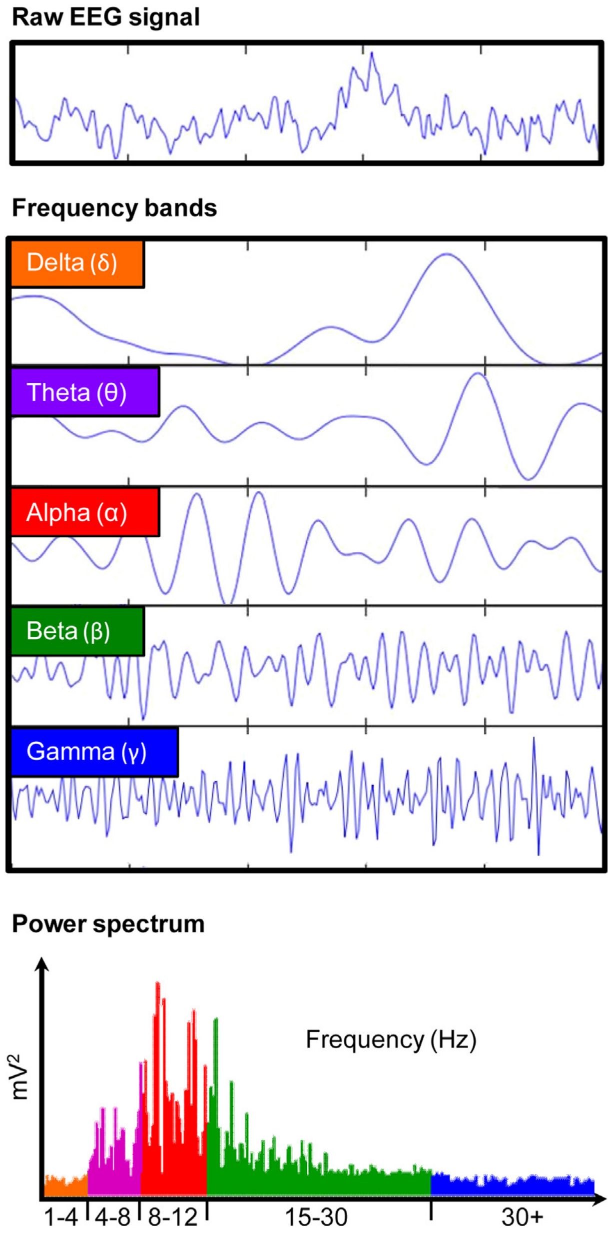

Fig. 2. Illustrates raw EEG data from a single channel and constituent frequency components, and includes a power spectrum for EEG recorded with eyes-closed, detailing commonly employed frequency limits for specific bands. Raw EEG and frequency components are shown as voltage (mV) over time, spectrum shows the power of frequency components (mV^2) for a specific segment of time. Raw EEG data and frequency components adapted from Heraz and Frasson (2011).

As we highlight below, however, existing EEG studies of sports performance have largely focused on cognitive explanations of expertise. In line with Fitts and Posner’s (1967) model, a wealth of behavioral evidence has associated peak performance (related to the final stage) with the subjective feeling of automaticity (e.g., Cohn, 1991; Anderson et al., 2014). Links between behavioral and neural markers of efficiency were first described in the field of cognition (Del Percio et al., 2011a), where higher levels of intelligence and superior performance have been associated with reduced cortical activation (Neubauer et al., 1995; Grabner et al., 2006; Neubauer et al., 2004). Consistent with this view, in the following section we review studies employing simple lab based tasks that contrast expert and novice athletes, demonstrating that increasing neural efficiency also underpins the development of sporting expertise.

2.1. Expert vs. novice performance

Studies comparing expert and novice performance have demonstrated that changes in alpha over specific regions of the scalp, are associated with skilled cognitive-motor performance in athletes: as such, alpha is thought to index changes in the neural response linked to training and the acquisition of expertise. Differences in eyes-closed resting state alpha rhythms have been observed between elite and amateur karate athletes and non-athletes, with an increase in parietal and occipital low-frequency (8–10.5 Hz) alpha for elite compared to amateur athletes and non-athletes; a result that was subsequently replicated with a group of rhythmic gymnasts (Babiloni et al., 2010). Whilst only a single condition was employed in these initial studies, with no baseline measure of alpha, similar results were found in a follow up study that directly compared eyes-open to eyes-closed conditions. In this case, compared to non-athletes, karate athletes exhibited reduced alpha ERD over frontal and central locations – a significant reduction of reactivity in the alpha band to eyes opening (Del Percio et al., 2011b). Although these neural differences were measured in simple lab based settings rather than during sporting behavior, they nonetheless provide tentative evidence of greater neural efficiency in elite athletes.

While these basic differences between athletes and non-athletes could suggest functional changes in alpha levels as a result of intensive training, based on published findings reported to date it is not possible to isolate a single cause driving the observed changes. For example, it is highly likely that athlete and non-athlete groups differ systematically in a number of important respects, many of which can influence brain activity, ranging from personality type (Tran et al., 2001) to levels of fatigue and drowsiness (Borghini et al., 2014). Such variability matters, because genetic, anatomical, physiological and psychological factors have all been shown to influence the power and prevalence of baseline levels of alpha in the EEG of individuals (for a review see Bazanova and Vernon, 2013). As such, observed differences in baseline (or activity related) alpha levels could be explained in terms of heritable genetic characteristics that are predictive of athletic competence, rather than tracking level of expertise as a function of intensive training.

Notwithstanding concerns about potential confounding variables when comparing different groups of participants, the use of simple lab based tasks also limits the interpretability of the results with reference to sporting behavior. Demonstrations of reductions in cortical activation using tasks more closely aligned with sport specific skills are, therefore, essential to elucidate neural factors underpinning development of expertise as a function of training. One approach is to measure alpha activity during the observation of sports specific actions. For example, compared to non-athletes, when viewing videos of real competition performances, rhythmic gymnasts have been shown to make more accurate 'judgments of quality' (compared to coaches ratings) and to exhibit lower levels of alpha ERD. Moreover, in rhythmic gymnasts, high frequency alpha (10–12 Hz) ERD was greater in magnitude for videos associated with high judgment error than for those associated with low judgment error (Babiloni et al., 2009). In this case, based on source reconstruction analyses the changes in alpha associated with expertise and performance were linked to different neural pathways (although the actual location of recorded changes in alpha were not reported). The gymnasts' greater experience and expertise is thought to underpin their ability to make judgments of quality, with a sub-band of alpha specifically tracking the accuracy of observations of sporting behavior.

An alternative to the observation of sporting behavior has been the use of basic motor tasks to directly compare levels of neural efficiency in athletes and non-athletes during behavior. For example, research has shown that elite fencing and karate athletes exhibit less of a decrease in alpha (over frontal, central, and parietal electrodes) than non-athletes for monopoladic (one-foot) standing (Del Percio et al., 2009a). Similarly, these athletes also exhibit reduced alpha ERD over the primary motor cortex during preparation and execution of wrist extensions (Del Percio et al., 2010). The use of basic motor tasks is a significant improvement on simple lab tasks, because they require behavior that is actually relevant to the chosen sport. Arguably, however, the observation of real sports provides a stronger link to the richness and complexity of sporting behavior. Regardless, neither approach provides a direct assessment of links between brain activity and aspects of sports expertise operative during real performance.

2.2. EEG activity during the pre-shot period

Studies designed to measure brain activity during performance have, to date, been limited to 'closed sports' (e.g., shooting, golf, archery, etc.), where issues of equipment portability and movement artifact are not a significant impediment. One reason that closed sports provide an ideal opportunity to measure active performance is that they typically involve fixed routines (e.g., target selection, shot execution), allowing neural activity to be segmented over time in relation to that behavior. In particular, researchers have focused on target sports, examining neural activity present in the seconds leading up to shot execution, known as the pre-shot period. For example, examination of brain activity recorded pre-shot during shooting shows that experts exhibit greater alpha power over left-temporal electrodes than novices (Haufler et al., 2000, 2002). Moreover, in skilled marksmen, this increase in left-temporal alpha power has also been shown to be progressive over the pre-shot period, being strongest just prior to trigger pull (Hatfield et al., 1984).

A number of studies investigating the pre-shot period in target shooting have shown that superior performance is related to an increase in alpha power over the left-temporal region of the scalp (for a detailed review see Janelle and Hatfield, 2008). Left-temporal cortex is typically associated with verbal-analytic and language functions, while right-temporal cortex is associated with visuo-spatial and integrative processing (Springer and Deutsch, 1998). Consequently, changes in alpha observed during pre-shot routines have been interpreted as reflecting a reduction in interference from overthinking (evidenced by increased left-temporal alpha), accompanied by the maintenance of visuo-spatial coordination (evidenced by right-temporal alpha being unaffected). In line with the Fitts and Posner (1967) model of skill acquisition, it is claimed that skilled marksmen have an enhanced ability to inhibit verbal-analytic processes (that may be necessary in the early stages of aiming, but ultimately interfere with performance if continued during execution), as indexed by increases in alpha power in the left hemisphere. However, other evidence challenges this view finding that really high levels of left-temporal alpha power and low beta power during the pre-shot period was associated with poorer performance in skilled archers (Salazar et al., 1990).

Evidence for performance related differences in alpha has also been identified in another sport – during the pre-shot period in golf. Fewer studies have been carried out with golfers to date, partially due to the potential for head movement artifacts, but focusing on the pre-shot activity during putting allows such artifacts to be minimized. For example, Baumeister et al. (2008) contrasted expert and novice performance during putting toward a target from 3 meters, over 5 sessions, each lasting for 4 minutes. Expert golfers performed better than novices overall, and better performance was associated with an increase in upper alpha power at parietal electrodes, along with an increase in theta power at frontal electrodes. The increase in frontal theta power for experts was interpreted as indexing more focused attention, while the increase in parietal upper alpha power was interpreted as reflecting better inhibition of irrelevant sensory information.

As well as differences between expert and novice golfers during the pre-shot period, differences in levels of alpha have also been demonstrated in the pre-shot period for successful and unsuccessful putts (Babiloni et al., 2008). In this study, expert golfers were required to execute 100 putts on a golf green simulator, from a distance of 2.1 meters. To ensure that at least 30% of putts were unsuccessful the diameter of the hole was adjusted for each participant (108 mm – standard, 80 mm, 60 mm). Results demonstrated increases in high frequency alpha ERD (10–12 Hz) for successful compared to unsuccessful putts over frontal and central midline (Fz and Cz), and right sensorimotor (C4), electrodes (see Fig. 3). Moreover, the reduction in alpha power correlated with the degree of error on unsuccessful putts, with stronger reductions associated with smaller degrees of error, as measured by the distance from the hole.

Whilst the preceding study once again provides evidence for changes in performance related alpha in a real sporting context, concerns with the findings cannot be ignored. From the perspective of sports practitioners, adjusting the size of the hole undoubtedly sacrifices some of the ecological validity gained by recording during actual performance. Moreover, from an EEG perspective, it is unclear why reductions in alpha power at electrodes Fz and Cz were not present in between, at electrode FCz, which would be expected to show a highly similar pattern. Perhaps more puzzling still is the fact that, rather than the previously reported increase in alpha, in this case superior performance was associated with a reduction in alpha power. Consideration of inconsistencies in findings reviewed thus far, both across sports and between studies, highlights the potential importance of characterizing functional relationships across cortical regions.

In a follow-up study, Babiloni et al. (2011) employed the same procedure reported above to investigate the functional coupling of alpha rhythms across electrode locations in expert golfers for successful and unsuccessful putts. Results revealed intra-hemispheric coherence in low frequency alpha (8–10 Hz) between parietal and frontal, and parietal and central sites in both hemispheres, an effect that was larger for successful putts. Comparable results were found for coherence of high frequency alpha (10–12 Hz) between frontal and parietal sites. Enhanced functional coupling of low and high frequency alpha between parietal regions, and temporal and occipital regions, has also been reported for elite air pistol shooters compared to non-athletes (Del Percio et al., 2011a). Taken together, these studies suggest that superior performance is associated with enhanced functional coherence of alpha rhythms prior to execution, consistent with the idea that expertise acquired over practice can elicit changes in the functional organization of the athletes' brain. Specifically, both of the studies outlined above link expertise with enhanced communication between visuo-spatial parietal sites and regions associated with motor control and attentional processing. However, whether changes in alpha coherence indicative of expertise vary as a function of sport or specific task demands remains an open question.

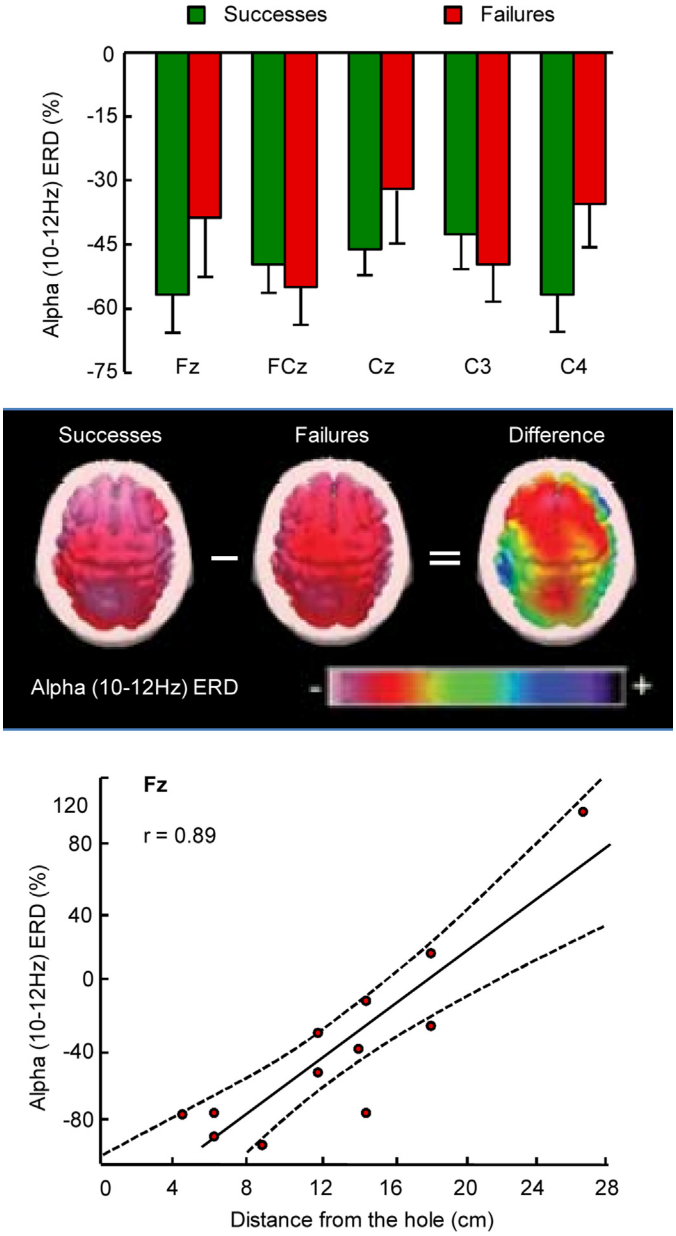

Fig. 3. Top panel shows the mean percentage of high-frequency alpha ERD at electrodes of interest. Middle panel shows scalp maps illustrating the distribution of high alpha ERD for successes and failures, along with the difference in distribution. Bottom panel shows the correlation between levels of high frequency alpha ERD and the degree of error (distance from the hole) on unsuccessful putts.

All adapted from Babiloni et al. (2008).

3. Issues and inconsistencies

Globally, the literature to date supports the view that changes in the alpha band are linked to differences in performance, but the specific details of the relationship remain unclear, in part because of inconsistencies in the direction of effects across studies. One possibility is that the cognitive effects of changes in alpha are themselves modulated by changes in other frequency bands (e.g., Salazar et al., 1990; see below in this section for further discussion). Alternatively, thinking of the relationship between alpha and performance as a simple linear function, where high degrees of alpha are always beneficial for performance, may underestimate the complexity of the relationship. In line with this assertion, it has been argued that lower levels of alpha indicate increased cognitive engagement, while medium levels index a reduction in this engagement moving toward greater automaticity of execution, and high levels indicate "cortical idling" which results in poorer performance (Deeny et al., 2003).

3.1. Methodological

In addition to variation in the direction of the relationship between alpha levels and performance outcomes, uncertainty is also introduced by inconsistencies in the scalp location where performance related changes in alpha have been reported for target sports. For example, in contrast to the left-temporal focus of alpha described above, a study of commonwealth level air-pistol shooters showed an increase in occipital alpha power preceding the best shots (Loze et al., 2001). Similarly, a study of pre-shot activity in elite air pistol shooters and non-athletes reported lower alpha ERD extending across frontal, temporal, parietal and occipital scalp locations for elite athletes, while an increase in the magnitude of upper alpha ERS (10–12 Hz) over right-parietal and left-central locations was associated with high score shots (Del Percio et al., 2009b). Contrasting aspects of the methodology employed in these two studies highlights a number of key problems that exist in the sports EEG literature in general, which complicates interpretation of the evidence to date.

Oscillations in the alpha range are associated with global communication and can, accordingly, be detected over the entire surface of the cortex (Nunez, 1995; Knyazev, 2007), and research has also demonstrated functional coupling between alpha measured at anterior and posterior locations (Srinivasan, 1999). However, fast (or upper) alpha rhythms are predominately generated in posterior regions, with slower (or lower) alpha rhythms predominately observed in anterior regions (Nunez and Katznelson, 1981). Importantly, differences in the location of reported alpha, and as a result apparent differences in cognitive functions associated with optimal performance in sport, are at least in part driven by the choice of electrode locations. In practice, the bulk of early target sports studies measured alpha from a small number of targeted recording sites (e.g., the study described above by Loze et al., 2001, employed 3 channels: T3, T4, Oz), whereas some more recent studies employ larger montages more typical of the wider EEG literature (e.g., the study described above by Del Percio et al., 2009b, employed 56 channels). Thus, given the ubiquitous nature of alpha across the scalp, differences in the number and location of electrodes across studies are likely to account for some of the apparent inconsistencies in the reported location of effects.

3.2. Analysis and interpretation

Alongside concerns about variability in electrode locations used in sports neuroscience studies, a number of wider concerns have been raised regarding the interpretation of brain oscillation data in general (e.g., Bazanova and Vernon, 2013; Cohen and Gulbinaite, 2014). Two specific challenges resonate strongly with work examining sports performance, namely, a lack of consistency in analysis strategy and a failure to address the potential for multi-scale interactions between different frequencies. Lack of consistency across studies is particularly apparent in the bandwidths used to define alpha, with some researchers splitting frequency bands into upper and lower portions (sometimes on a person-by-person basis, the so-called 'individual alpha frequency' strategy), and others reporting data for entire bandwidths (chosen based on an *a priori* basis). Another prominent source of inconsistency lies in the choice of baseline period: reported increases or decreases in band power are dependent upon the baseline used as a starting point (e.g., consider the use of eyes-closed supine versus eyes-open upright-standing as potential baselines in relation to observation of performance).

More broadly, existing studies of sports performance typically focus primarily, if not entirely, on alpha – ignoring the fact that changes in specific frequency bands do not occur in isolation and can often be reciprocal in nature. For example, a negative relationship between alpha and delta oscillations has been identified, such that increases in alpha are accompanied by decreases in slow-wave delta (Robinson, 1999). The presence of multiple frequencies, and the possibility of interactions between frequencies, are generally underappreciated or ignored within the sports literature. As such, at this stage, it is difficult to assess whether inconsistencies in findings for target sports relate to differences in task demands or are merely a product of differences in method, terminology or analysis strategy. In general, future work in sports should adhere more closely to existing guidelines detailing accepted standards for recording and analysis of EEG data in the wider literature (e.g., see Picton et al., 1995, 2000; Sharbrough et al., 1991), and give careful consideration to sport specific challenges raised by recording EEG data during motion (see Thompson et al., 2008). Notwithstanding the issues outlined above, findings to date do, overall, support the presence of a relationship between alpha levels and optimal performance in target sports.

Overall, the preceding sections highlight both similarities and differences in patterns of alpha activity found across studies. While evidence for the role of alpha in sporting expertise has consistently been reported, it is equally clear that results are somewhat variable (e.g., in the location and direction of changes in alpha). As already noted (see Section 2.1) physiological, developmental and psychological factors can all influence frequency components, providing many opportunities for confounding factors in between group comparisons. For example, groups of novices are highly likely to be more heterogeneous in their behavior than groups of experts, potentially resulting in neural differences regardless of factors related to expertise (cf. Chuang et al., 2013). Wide adoption of the expert/novice paradigm, and a broader reliance on between group comparisons, is in part driven by the main goal of cognitive neuroscience: to identify brain-behavior links that hold for populations as a whole. While useful in identifying basic neural mechanisms that characterize expert performance across a variety of sports, reliance on between group contrasts also means that the literature to date has largely failed to address the main goal of sports science: to assess and enhance performance in individual athletes. Before returning to the issue of person-specific assessment in the context of tailored neurofeedback protocols, the following section first introduces an alternative approach to examining performance related brain activity.

4. EEG in the time domain: ERPs and stages of processing

A comparatively small number of sports performance studies have examined neural activity in the time domain, mapping changes in EEG to particular event milestones by forming Event-Related Potentials (ERPs). ERPs reveal changes in activity specifically associated with an event of interest (e.g., seeing a stimulus or making a response), typically characterized as modulations in the amplitude (i.e., magnitude) of activity measured over a particular period of time, at specific locations over the scalp, when contrasting across experimental conditions (see Luck, 2005). Time and frequency based analyses provide complimentary insights into the neural basis of behavior, and in principle the same EEG data can be examined in both domains. The findings cannot always be readily compared, however, in part because the temporal precision employed with the two methods differs. Whilst frequency data is typically measured over seconds, ERPs are used to track changes in activity over tens or hundreds of milliseconds – aligning well with the rapid timecourse of sporting activity. As a result, studies in the time domain have largely examined two broad categories of ERP effect relevant for sporting action; which are reviewed in turn below.

4.1. Preparing, inhibiting and executing

A number of ERP studies have focused on well-characterized neural correlates of movement, namely readiness potentials, related to preparation for making a response, and motor potentials, related to the actual execution of the response. When participants are required to make motor responses (e.g., finger, arm or leg movements) the period preceding the execution of the movement is associated with sustained changes in brain activity – a gradual reduction in electrical activity is followed by a sharp spike in activity that can be measured from electrodes positioned over motor cortex (e.g., C3 and C4). For example, compared to amateurs and non-athletes, elite table tennis players exhibit an increase in the amplitude of readiness potentials measured during performance of a Posner-style attention task (Hung et al., 2004). In this study a mixture of valid and invalid directional cues were presented to participants, indicating the location of a subsequent target stimulus; modulations were observed in the response preceding the target at electrodes located over sensorimotor areas for the hand corresponding to the side of a directional cue. This finding was interpreted as reflecting 'superior reactivity' as a function of sports specific expertise, presumably because table tennis players use movement cues from opponents to predict the trajectory of the ball during play. However, use of a standardized lab based test of attention employing abstract cues unrelated to sporting context is clearly not equivalent to reading complex movement cues during performance, making links to sports specific skills somewhat tentative.

Differences in movement potentials have also been reported by studies employing simple lab tasks more closely aligned with sports specific skills. For example, compared to non-athletes, elite rifle shooters have been shown to exhibit a reduction in movement related cortical potentials measured during self-paced finger movement (Di Russo et al., 2005). In this case, participants were required to perform flexion movements by pressing buttons on a response pad, alternating between left and right index fingers between trials. ERPs were time locked to movement onset and revealed differences between athletes and non-athletes in the latency and amplitude of movement potentials only for right finger flexion (the finger used for shooting). Potentials associated with preparation and execution of voluntary movement (i.e., the Bereitshaftpotential [−1500 to −500 ms] and Negative Slope [−500 to −50 ms]) were longer and smaller in amplitude over central left-hemisphere locations in rifle-shooters than for controls. This study is notable for targeting specific aspects of physical control thought critical for rifle shooting. As for many of the simple lab based tasks discussed earlier however, no direct reference was made to sporting context, leaving it difficult to assess whether differences between athletes and non-athletes are related to expertise acquired via training or heritable traits predictive of expertise.

Analogous to the transition from simple lab based tasks to more realistic sporting behavior described above for frequency domain studies, neural changes in the response of experts during the observation of sports specific actions have also been revealed with ERPs. For example, when presented with pictures of real attacks performed by elite athletes, and asked to indicate the side of attack, fencing and karate athletes have been shown to exhibit differences in movement related potentials compared to non-athletes (Del Percio et al., 2008). Here, ERPs were averaged time locked to the onset of the motor response and analysis focused on potentials associated with preparation (readiness potential) and initiation of movement (motor potential) over central locations (C3, Cz, C4) during the −1500 to −500 ms time interval preceding response. Results revealed a reduction in the amplitude of readiness and motor potentials in athletes, for right movements over supplementary motor (i.e., Cz) and contralateral sensorimotor (i.e., C3) locations for both classes of athletes compared to non-athletes, and higher amplitude motor potentials over the ipsilateral sensorimotor location (i.e., C4) for karate than for fencing athletes. Much like findings from studies examining changes in alpha, these ERP findings were interpreted as supporting greater neural efficiency as a function of training in elite athletes, whilst highlighting that the development of neural efficiency in motor preparation and execution can depend upon the side of movement and may also be sports specific.

As the preceding review highlights, the results from ERPs studies examining movement potentials are somewhat variable, with both increases and decreases in the amplitude of readiness and motor potentials associated with sporting expertise. Changes in the pattern of results across studies could, of course, merely reflect sport specific differences. Regardless, the variable nature of the findings appears to stand in opposition to broader claims that there is a direct mapping between the development of sporting activity (as indexed by increasing levels of expertise) and neural efficiency (as indexed by reductions in brain activity). Evidence contradicting claims of a relationship between greater neural efficiency and higher expertise is, however, not limited to the sporting domain; in the wider cognitive neuroscience literature better performance has been associated with both increases and decreases in activation (Gray et al., 2003; Haier et al., 2004). Clearly, care must be taken when interpreting changes in the amplitude of ERP (or power of frequency) effects; some aspects of the signal may reflect inhibition, while others may simultaneously reflect increased activation. In addition to varying as a function of level of expertise, whether patterns of activation, inhibition, or both are observed may depend upon specific task demands and the exact nature of the sport in question (Del Percio et al., 2011b). While findings relating to movement potentials are mixed, studies examining ERP effects related to stimulus detection and response selection have produced more consistent results.

4.2. Detection, evaluation and selection

Consistent changes in patterns of brain activity for athletes compared to non-athletes have been reported by studies employing Go/No-go paradigms. Used in the wider literature to investigate aspects of response control, this procedure involves the presentation of a series of cues that signal either action (Go trials) or inhibition (No-go trials), with ERPs recorded time-locked to the presentation of different cue types. When examined in typical (i.e., non-sports) populations, increases in the amplitude of N200 (a negative deflection occurring ~200 ms after stimulus onset linked to stimulus detection) and P300 (a positive deflection ~300 ms after stimulus onset linked to stimulus evaluation) potentials are commonly found for No-go trials, and are largely thought to reflect aspects of response inhibition in this context (e.g., Falkenstein et al., 1999; Bekker et al., 2005; Oddy et al., 2005). A similar pattern of results has also been found in between-group comparisons of athletes and non-athletes. For example, contrasts between difference waveforms (Go minus No-go) has shown that elite fencing athletes exhibit larger N200 effects at frontal locations, and larger P300 effects at frontal and parieto-occipital locations, than are seen for non-athletes (Di Russo et al., 2006). While supporting the view that expertise is facilitated by better attention to task relevant stimulus features and enhanced inhibition of planned responses, once again the findings come from a study employing a simple lab based task, with four abstract geometric configurations to signal Go/No-go activity, making no reference to real sporting behavior.

The importance of examining neural activity in sports-relevant contexts is highlighted in a study by Nakamoto and Mori (2008). Here a lab based Go/No-go task was employed, comparing performance of baseball players and non-athletes, while manipulating the sports-relevance of task cues. In a baseball condition, specific spatial locations acted as a cue for response execution or inhibition (with the intention of mimicking cues provided during batting), whereas in the remaining experimental conditions responses were made based on arbitrary stimulus location or color (see Fig. 4a for schematic illustration of experimental conditions). ERPs, time locked to stimulus onset, were formed for each group, condition and response type, and analysis focused on readiness potentials (from −600 ms prior to response), P300 effects for Go trials (280–500 ms) and N200 and P300 effects for No-go trials (150–250 ms, 280–500 ms). Results revealed that for the baseball specific condition, readiness potentials were shorter lived for the baseball group than for the control group, providing evidence for a domain-specific advantage in motor preparation for expert players. In addition, for baseball players, P300 effects were larger in amplitude for No-go trials in the baseball specific and color conditions, but were more pronounced at frontal sites for the baseball specific condition, suggesting enhanced attention to sport-relevant cues (see Fig. 4b). Taken together, these findings were interpreted as providing evidence for domain specific response selection and stronger inhibition as a function of expertise.

While the preceding study specifically aimed to examine sport specific changes in neural activity, it still failed to fully capture the dynamic nature of real-world baseball performance. A more realistic approach was adopted by Nakamoto and Mori (2012) in a baseball simulation study investigating movement correction and the rate of motor reprogramming in expert and novice players. An electronic trackway with LED lights was used to simulate the approach of a moving target (see Fig. 5a), and the velocity of the target was manipulated by introducing an occasional unexpected slow ball simulation. ERPs were formed for fast and slow ball simulations, time locked to the onset of velocity change on slow balls, and fast ball ERPs were subtracted from slow ball ERPs to eliminate common activations. Results revealed that when presented with slow balls, baseball experts exhibited faster onsetting N200 potentials over central locations, along with a delay in the peak latency of P300 potentials, and an increase in the amplitude of P300 potentials over frontal locations (see Fig. 5b). Extending the findings from the previous study, results were interpreted as reflecting faster stimulus detection and stronger inhibition of planned responses in experts.

Overall, the ERP studies reported in the preceding section demonstrate that it is possible to identify patterns of brain activity related to specific stages of behavior. Moreover, these neural mechanisms have been shown to be sensitive to sporting expertise. Evidence suggests that sensory, cognitive and motor processes underlying skilled behavior in general, can also be identified as playing a significant functional role in expert sporting performance. As with work carried out to date in the frequency domain, however, ERP studies largely fail to address the complexity of real-world sporting activity. Understanding expert performance and the development of sporting behaviors through research applications of mobile EEG clearly presents an opportunity for paradigm change. The ability to capture neural signals and motor behavior measures within ecologically valid environmental conditions will form one basis for new understanding. At the very least, measuring actual sports performance, rather than performance on abstract laboratory tasks (as the majority of existing studies have done) is likely to lead to significant advances in understanding.

Our review also reveals a clear opportunity for mobile EEG to be used to ask different kinds of questions to those traditionally asked by cognitive neuroscientists, more aligned to issues of interest to sports professionals. For example, from a sports perspective it is of interest to examine longitudinal changes in EEG within individuals – both as a basis for assessing changes in performance with practice or coaching, but also for the purpose of identifying talent.

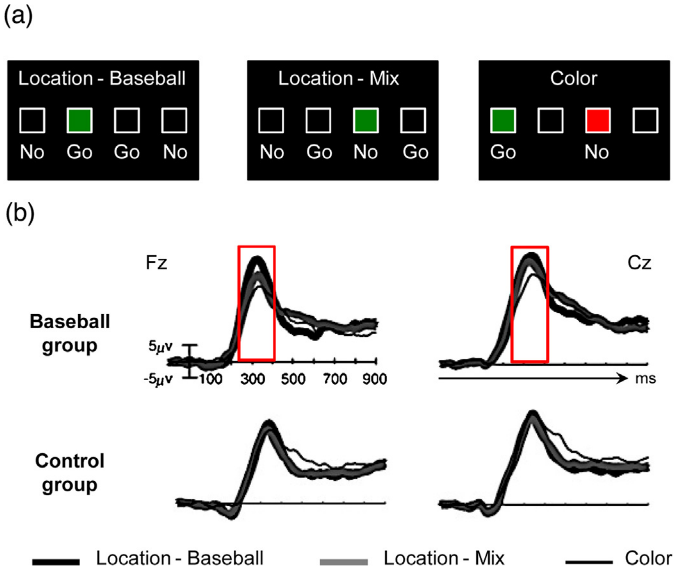

Fig. 4. (a) Procedure: each panel illustrates a specific stimulus–response mapping highlighting the position of Go and No-go trials across conditions designed to manipulate baseball relevant processing. (b) Results: grand-average ERP waveforms for each condition on No-go trials for the baseball and control groups at electrodes Fz and Cz. Boxes highlight differences in P300 effects that were evident only for the baseball group.

Adapted from Nakamoto and Mori (2008).

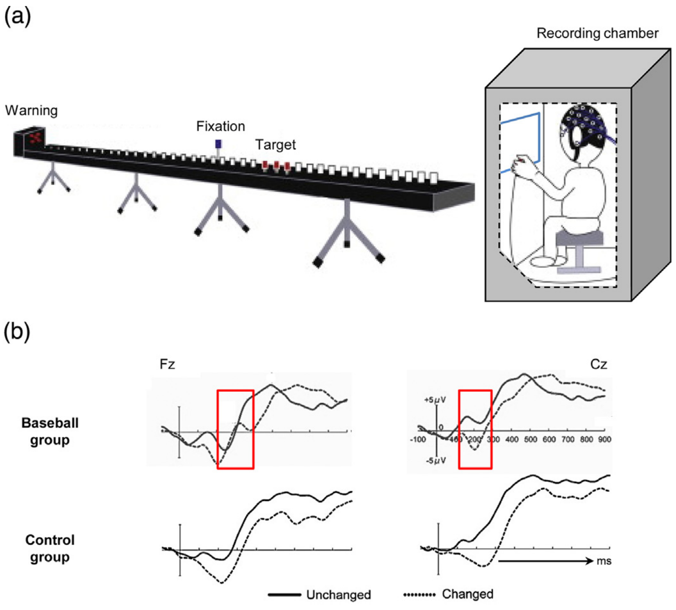

Fig. 5. (a) Procedure: schematic illustration of experimental apparatus used to simulate the approach of a moving target for baseball players. (b) Results: grand-average ERP waveforms for changed and unchanged velocity conditions in the baseball and control groups at electrodes Fz and Cz. In comparison to controls, data for the baseball group evidenced earlier onsetting N200 potentials over central locations, along with delayed P300 potentials at frontal locations that were larger in amplitude.

Adapted from Nakamoto and Mori (2012).

Ultimately, effective sports neuroscience measures should allow the selection and development of talented individuals. As noted earlier in the introduction, mobile EEG technology has advanced sufficiently to open up research in this area; before outlining these technological developments in more detail, the following section will provide a selective review of the evidence supporting the application of neurofeedback techniques in sport.

5. Neurofeedback

Neurofeedback is a conditioning technique employed to teach participants to modify their own neural activity, by facilitating the recognition of specific mind/brain states associated with particular (i.e., desired) behavioral outcomes. In a typical neurofeedback paradigm, participants have their EEG measured continuously and a representation of their brain activity is communicated back to them (see Fig. 6). Frequency analysis of the EEG is commonly used to provide a rolling estimate of the power of particular bands (e.g., alpha, theta), and power levels can be shown graphically, represented by auditory tones, or via some form of illustration (e.g., a balancing scale or moving ball). Over time, participants are able to learn how their internal mental state correlates with the neural signal, allowing voluntary control to be exerted over entry to, and maintenance of, particular states. A number of neurofeedback protocols have been developed, relying on different neural signals, and used in different contexts. For example, Alpha-Theta (A/T) training is often employed to encourage relaxation and reduce anxiety, by requiring participants to raise levels of theta over levels of alpha (e.g., see Peniston and Kulkosky, 1991; Raymond et al., 2005) or raise levels of alpha and theta together (e.g., see Peniston and Kulkosky, 1989). By contrast, Sensory Motor Rhythm (SMR: see Kober et al., 2014) training is used to reduce motor interference and enhance cognitive performance, and participants are commonly required to raise SMR (12–15 Hz) levels whilst controlling beta levels.

Neurofeedback was originally applied in clinical contexts (e.g., Lubar and Shouse, 1976), with the aim of treating various psychological disorders, including anxiety, depression, Post-Traumatic Stress Disorder (PTSD) and Attention-Deficit Hyperactivity Disorder (ADHD). However, the goals of neurofeedback in clinical populations differ dramatically from those of performance enhancement in sport, where the aim is to take normal patterns of activation and make them optimal (Wilson and Peper, 2011). Indeed, rather than being interested in changes in neural patterns per se, the aim for sports is simply to achieve changes in performance outcomes. Initial evidence supporting the viability of neurofeedback techniques for performance enhancement in normal populations came from work demonstrating that increasing power in specific frequency bands led to enhanced cognitive performance (e.g., Hanslmayr et al., 2005). While the potential to use neurofeedback for performance enhancement in sport has been recognized for some time, progress to date has been limited by a lack of adequately controlled studies. Historically, however, criticism of neurofeedback techniques on these grounds has not been limited to the field of performance enhancement in normal populations; a general lack of validity was also apparent in early work with clinical populations.

Recently, evidence has begun to accumulate validating the use of specific neurofeedback protocols for enhancing aspects of cognitive function in both clinical and normal populations, driving renewed interest in the potential of neurofeedback techniques in general (e.g., Bazanova et al., 2009; Nan et al., 2012; for discussion and review see Gruzelier, 2013). In the context of optimizing aspects of sporting performance, however, application of neurofeedback still awaits thorough validation. Somewhat surprisingly, despite dramatic growth over the last decade in the number of sports related neurofeedback studies, some of the strongest evidence supporting the efficacy of the technique still comes from the earliest work in the field. For example, Landers et al. (1991) studied the effectiveness of neurofeedback training using 24 pre-elite archers randomly split into three treatment groups. Alpha levels were recorded whilst participants made a series of shots, and neurofeedback was provided visually. The correct feedback group received a single session of training where the goal was to reduce left-temporal (T3) activation; the incorrect feedback group received training to reduce right-temporal (T4) activation, and the control group received no training. As would be expected, based on previous findings demonstrating that left-hemisphere alpha levels are associated with expertise (see Section 2.2), the correct feedback group showed an improvement in performance following training, whilst the incorrect feedback group showed poorer performance post-training, and scores for the control group did not differ. Despite this early positive demonstration, however, contemporary research has made limited progress in supporting the efficacy of neurofeedback in sporting contexts.

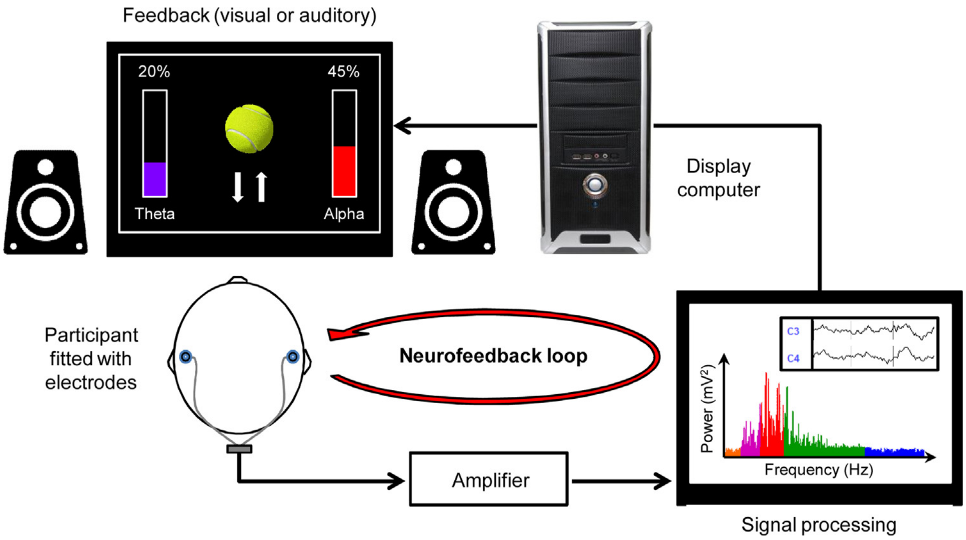

Fig. 6. Schematic illustration of laboratory set up for neurofeedback training. Neural signals are processed in real-time and participants are typically given auditory or visual information on current status, to facilitate modification of mental states.

In a recent study, for example, Brown et al. (2012) employed a standardized SMR training protocol to enhance the accuracy of serves in 10 elite table tennis athletes and demonstrated a trend toward greater accuracy following neurofeedback training. Unfortunately, this effect failed to reach statistical significance, and the authors did not employ a control group, making it difficult to interpret the results. Failure to find significant changes in performance measures or patterns of brain activation following neurofeedback training is not, however, uncommon. For example, Dekker et al. (2014) employed self-guided eyes open alpha training over 10 sessions in 12 elite gymnasts in a double-blind and placebo-controlled study. For the treatment group neurofeedback was provided by linking alpha power to the auditory sound quality of music played to participants. Results failed to demonstrate either a significant benefit of training, or differences in baseline alpha levels between treatment and control groups post-training. One potential concern for interpreting the results of this study is that music itself affects the cognitive and psychomotor functions involved, potentially making any additional benefits of neurofeedback difficult to identify. The study does, nonetheless, highlight that validation of neurofeedback techniques in sport is still lacking. In short, these studies fail to provide substantial behavioral or neural evidence that supports the validity of neurofeedback training.

One potentially critical difference between these three studies is the level of athletes employed, with significant results only found for pre-elite athletes (i.e., Landers et al., 1991). Whilst improvements in performance are, in principle, more difficult to observe in elite athletes (due to their existing high levels of expertise) than in pre-elite or amateur athletes, significant benefits of neurofeedback training have, nonetheless, been reported for elite athletes. In a longitudinal study, Rostami et al. (2012) compared the performance of 24 elite rifle shooters over the course of five weeks; half formed a treatment group, receiving 3 sessions (60 minutes) of SMR neurofeedback training per week, while the remainder formed a control group receiving no training. The authors found a significant improvement in shot results for the neurofeedback group when assessed post-training, but no difference in the control group. Interestingly, although the two studies described that have reported significant improvements employed different training protocols, they both focused on target sports – suggesting that the potential efficacy of neurofeedback may partially depend on the nature of sport specific task demands. Equally, it is plausible that the predefined neurofeedback protocols employed in these studies may align with aspects of function that are more crucial for performance in target sports than for sports such as table tennis and gymnastics. While delineating between these potential explanations lies beyond the scope of the current review, the preceding discussion hints at the need to develop sports specific training protocols.

Regardless of whether standardized neurofeedback protocols turn out to be valid only for a subset of sporting behaviors, the studies reviewed above all attempt to characterize the benefits of neurofeedback at a population level. As noted above, however, a more critical issue for sports practitioners is to enhance the performance of individual athletes. Elite athletes are necessarily outliers – they have acquired a level of expertise that cannot be accounted for by practice alone. Indeed, a large number of athletes can complete comparable training regimes as amateurs, but only a handful will go on to develop expertise worthy of elite status. Consequently, one critical question from the point of view of the sports practitioner is whether patterns related to success in different sports are trainable via the application of EEG based neurofeedback on an individual basis. Inter-individual differences in baseline frequencies suggest that the optimal pattern of training should not only be sport specific, but should also be individually tailored.

Despite a number of authors commenting on its necessity (e.g., Hammond, 2007), to our knowledge only one study published to date has assessed the application of individually tailored neurofeedback training during performance. In a novel and technically ambitious study, Arns et al. (2008) created personalized profiles for 6 amateur golfers based on EEG recorded from electrode FPz during the execution of 80 assessment putts. Activity profiles were formed by averaging EEG across the assessment putts, and then identifying frequency bands that exhibited differences in power between successful and unsuccessful putts during a 1-second pre-shot period. These personal profiles were then applied during three sessions, on three consecutive days. During training a tone was used to indicate when the optimal neural pattern had been achieved, providing a signal that the putt should be executed. On each day participants performed four sets of 80 putts that alternated between no training and training conditions in a blocked design. Results demonstrated the presence of significant increases in putting accuracy for training compared to no training blocks on day 2, but no benefit of training was observed for day 3, with performance being lower overall than on day 2 (see Fig. 7). In principle, this study illustrates the ideal use of neurofeedback, yoked closely to active sporting behavior – with the aim of enhancing performance on an individual level.

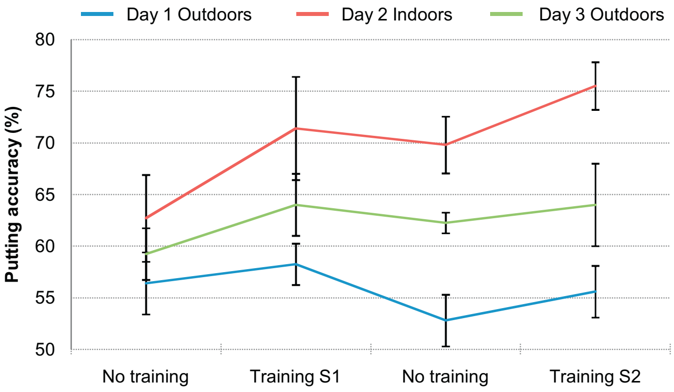

Fig. 7. Percentage of successful putts over three days for training and no training sessions. Significant improvements in performance were observed for both training sessions on day 2 compared to the first no training session.

Adapted from Arns et al. (2008).

Although promising, the findings reported by Arns et al. (2008) are not definitive, at least in part because the effects of neurofeedback were variable. The poor performance and absence of benefit seen for sessions 1 and 3 could have resulted from putting taking place outdoors (compared to indoors for session 2). Arguably, outdoor conditions are associated with greater variability (e.g., due to changes in lighting, wind, etc.) resulting in more difficult task demands in the outdoor sessions. Regardless, a greater concern is the fact that whilst neurofeedback measures were tailored to each individual, performance measures were not reported individually, making it difficult to assess fully links between neural profiles and performance enhancement. Notwithstanding these concerns, the current study is the first to demonstrate that personalized EEG profiles related to success can be identified in the pre-shot period and, tentatively, that they could be used to enhance performance in individual athletes.

It is clear from the preceding discussion that findings from the application of neurofeedback during sporting performance are mixed, and further work in this area is warranted before firm conclusions about the efficacy of neurofeedback can be reached. In a recent extensive review of the wider literature on neurofeedback, Gruzelier (2014) identified a range of methodological flaws, highlighting three key criteria for demonstrating the validity of neurofeedback (i.e., specificity of frequency band, behavioral outcome and topographic distribution). In depth discussion of these issues and other factors influencing the efficiency of neurofeedback training (for discussion see Vernon et al., 2009; Alexeeva et al., 2012; Bazanova, 2012) lie beyond the scope of the current review, however, it is clear that validity conditions have not yet been fully addressed in the domain of sports neuroscience. For example, studies have focused on demonstrating improvements in behavioral performance, without aiming to demonstrate post-training changes in the targeted frequency. While application of neurofeedback in sports is still in its infancy, lessons can clearly be learned from the established literature in other areas. Ultimately, neurofeedback has great potential as a training technique to enhance performance in sports, but still requires detailed investigation and validation. At this stage, an essential requirement is to better characterize differences in factors across sports, and between individuals competing at the elite level, to provide an adequate knowledge base for effective application of neurofeedback techniques, by measuring EEG during active sports performance.

6. Toward a mobile cognition approach

Over the course of this review we have highlighted that different patterns of neural activity are observed when sports relevant activity is examined, compared to when simple lab based tasks are employed. Consequently, if significant progress is to be made in the field of sports neuroscience, imaging data needs to be collected whilst athletes engage in real active sporting behavior, using ecologically valid paradigms. Real-world EEG data collection creates a number of specific requirements however, including portability of the equipment, ease of application and the ability to effectively handle motion artifacts. From the perspective of sports practitioners, it is critical that mobile EEG equipment and procedures do not impede sporting activity, or lead to significant interruptions during training. From a neuroscience perspective, data quality is paramount, and mobile systems must be able to deal with motion artifacts effectively, whilst closely matching the performance of a lab-based setup. Fortunately, as we outline below, over the last decade there have been significant developments in mobile EEG technology that overcome many prior limitations and promise to make real-world recording a routine practice.

The main advance in technology facilitating the movement of EEG from the lab into the real-world has been the development of small lightweight battery powered amplifiers. Recorded data is typically saved to a portable hard-drive for later review and analysis off-line, but can also be transmitted wirelessly in real-time to a PC or handheld device for on-line viewing. Consumer technology currently available on the market includes wearable headsets designed primarily for Brain Computer Interface (BCI) applications (e.g., Emotiv [Hong Kong, ROC]; Neurosky [San Jose, CA, USA]). Smaller devices also exist, employing a limited number of electrodes (i.e., that can be worn on a headband or on a belt around the waist), designed primarily for use in psychophysiological monitoring and neurofeedback applications (e.g., B-Alert X series [Advanced Brain Monitoring, Carlsbad, CA, USA]; Neurobit Systems [Gdynia, Poland]). These devices were primarily developed for personal applications such as gaming and health monitoring rather than for use in research *per se*. Nonetheless, the rapid development of commercial equipment has demonstrated that it is possible to produce truly mobile EEG technology, meeting the portability requirements of sports practitioners. However, despite enthusiastic adoption of mobile EEG across a range of applications, the validity of these systems for use in pure research applications was largely unaddressed.

At this stage, work validating mobile EEG technologies for use in pure research applications is ongoing, but initial signs are promising. The bulk of studies to date seeking to validate mobile EEG technology have focused on P300 effects, which provide a highly reliable signal, observable even at a single trial level (e.g., Debener et al., 2002; Blankertz et al., 2011). Whilst relevant for sporting behavior, the focus on P300 effects in validation studies is primarily driven by the utility of P300 effects for BCI research. For example, a recent BCI study directly compared wireless mobile and traditional fixed amplifiers using a simple lab based task. Results revealed a high degree of correlation in the amplitude and topography of P300 effects across systems, suggesting that it is now possible to capture comparable EEG data using mobile amplifiers (De Vos et al., 2014a). Whilst this study is important as a test of the basic validity of the mobile equipment, demonstrating that a known neural signal can be accurately measured, it does not address a key requirement: the ability to record clear signals during motion.

A clear demonstration that reliable P300 effects can be obtained during motion has been provided by studies employing oddball tasks (i.e., where participants are required to report infrequent targets presented within a stream of frequent non-targets). For example, using EEG recorded indoors whilst seated versus outdoors whilst walking, reliable single-trial P300 effects were obtained using an auditory oddball task (Debener et al., 2012). In this case the wireless setup used dry electrode sensors taken from a commercial Emotiv headset, fitted into an elasticated cap with a small head mounted amplifier. Importantly, these findings were replicated in a more recent study employing the same mobile equipment while participants walked freely outdoors (De Vos et al., 2014b). Taken together, these studies confirm the validity of mobile EEG technology for capturing P300 effects during motion. While further validation will be required to assess measurement of other sports-relevant patterns of brain activity in the field, current findings support the view that advances in mobile equipment now make this a genuine possibility.

Along with advances in EEG mobile technology, progress in signal processing has also made it possible to address some of the issues traditionally associated with capturing neural data in active sporting contexts (for discussion see Thompson et al., 2008). In particular, spatial filtering techniques such as Independent Components Analysis (ICA) can be applied to ERP data to dissociate brain activity from movement artifacts. In basic terms, ICA uses the correlational structure of a dataset to decompose the observed ERP waveform into a set of statistically independent constituent components that can then be apportioned as either signal of interest, or noise (e.g., Vigário et al., 2000). Using an ICA approach, Gramann et al. (2010) contrasted ERPs recorded using standard equipment during a visual oddball task with four movement conditions: performed on a treadmill, standing, slow walking, fast walking and running. Whilst the data from the running condition was excluded due to the presence of large mechanical artifacts caused by movement in the cabling, results evidenced comparable P3 effects across the remaining movement conditions, demonstrating that reliable effects can be obtained during moderate whole body movement.

Overall, the evidence to date supports the view that developments in mobile EEG technology and progress in signal processing now make it possible to monitor brain activity during active sports performance. Moreover, recently, mobile EEG equipment aimed specifically at sporting applications has become commercially available that can record up to 64-channels of high resolution EEG – providing recording capabilities that have only been found in lab-based systems to date (Eegosports [AntNeuro, Enschede, Netherlands]). The combination of practical and technical developments means that EEG can be recorded whilst athletes engage in normal sporting activity (see Fig. 8), ranging from playing a round of golf to riding a bicycle. Whilst limits do still apply (e.g., recording during swimming or high-impact sports such as running), it is clearly possible to monitor brain activity without significantly impeding the execution of a range of sporting behavior. The use of mobile EEG data in active sporting contexts is, of course, likely to

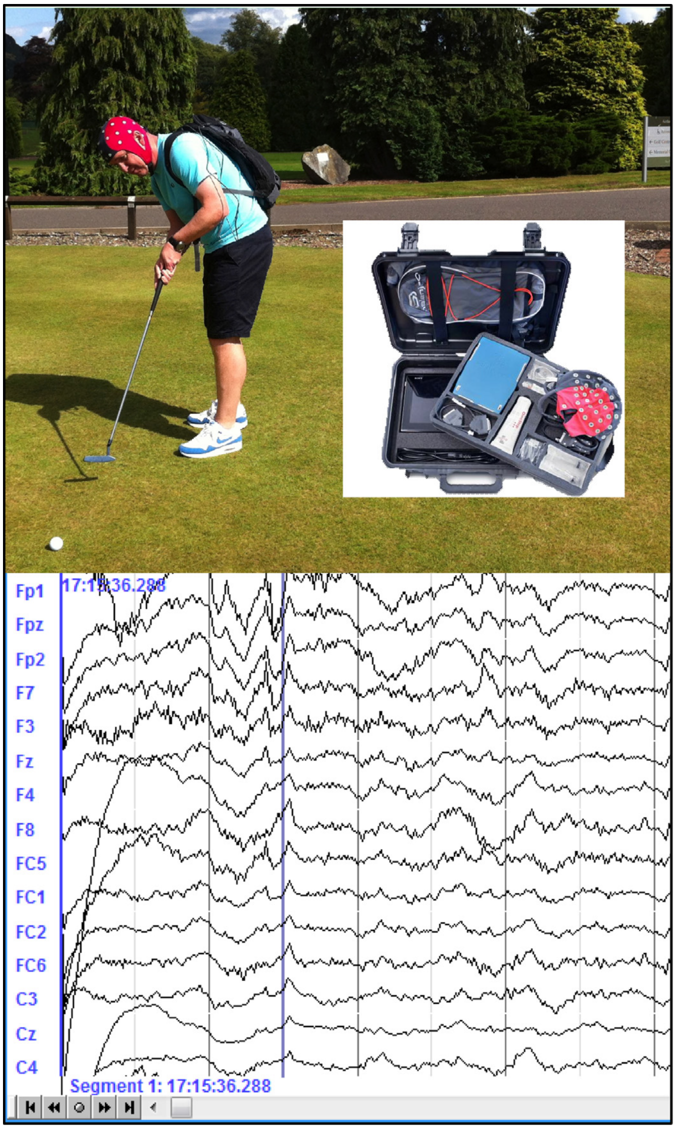

Fig. 8. Mobile EEG in sporting contexts. Developments in technology now make it possible to obtain full scalp coverage in the field, without impeding sporting behavior, and equipment is flexible enough to be well suited for use across a range of sporting applications (top). EEG data shown were recorded during the golf-putting task pictured above, providing an illustration of data quality during performance.

reveal new technical and methodological challenges. Equally, however, mobile EEG offers new opportunities for sports, including the ability to track the brain activity of individual elite athletes, over extended periods of time.

7. Conclusion

Despite early recognition of the potential utility of brain imaging for sports, the application of EEG techniques to assess factors contributing to performance is still in its infancy. A number of limitations of work carried out in the literature to date have been highlighted over the course of this review, including a general lack of ecological validity, critical differences in methodology, a lack of consistency in analysis strategy, and failure to address individual differences. Here we highlight two issues of particular concern. First, at present, a disconnect is often apparent between the evidence provided by EEG studies, and the functional interpretation of the findings. For example, changes in alpha are interpreted as reflecting changes in a range of different mechanisms, motivated largely by *a priori* descriptions of the specific sport under investigation. Secondly, neurofeedback studies largely fail to report changes in brain activity related to training, as improvements in behavioral performance outcomes are of primary interest from the perspective of sports practitioners. Notwithstanding these limitations, studies to date do provide consistent evidence of neural correlates linked to optimal sporting performance.

In the time-domain studies link expertise in response evaluation and motor output with modulations of P300 effects and readiness potentials, whilst in the frequency domain changes in alpha levels are linked to development of expertise and performance outcomes. One problem with work in this area is that it has primarily focused on alpha rhythms, despite evidence from the wider literature linking changes in other frequency bands with cognitive functions highly relevant to sports performance. For example, gamma (>30 Hz) oscillations are modulated by sensory input and have been linked to working memory, learning and attention (Jia and Kohn, 2011), and theta oscillations have been associated with cognitive control and response inhibition (for a recent review see Cavanagh and Frank, 2014). Progress in unraveling brain-behavior links during complex sporting performance, requires future research to address these gaps in the literature, and in doing so, appreciate that complex brain functions are potentially supported by the combined action across frequency bands (Başar, 2008). Notwithstanding this requirement for future research, on the basis of the evidence reviewed here, it is clear that EEG measures have great potential to provide insight into the neural underpinnings of expertise and optimal performance in sport.

While findings from EEG research with athletes have had limited impact for sports practitioners, new opportunities afforded by mobile technology are encouraging renewed interest from the sporting world. Whilst it has been argued that "there will be no emerging field of neuro-sport" (Walsh, 2014), we disagree. The development of mobile technologies allows cognitive neuroscientists to move out of the laboratory, examining real sporting behavior in action. We believe that mobile methods add significant value to traditional fixed methods, and open sport up to investigation. On that basis we believe sports neuroscience will make progress. Moving EEG out of the lab and onto the training field has the potential to not only facilitate better understanding of brain-behavior links, but also to produce new advances in sporting practice. From a neuroscience perspective, measurement of performance in the field has a number of potential advantages. In the first instance, the high degree of ecological validity would provide a more stringent test of the neural efficiency hypothesis, and is likely to promote discovery of additional factors implicated in performance that are not apparent in controlled laboratory studies. In addition, combined with sound methodology, longitudinal tracking of individuals over the course of training with mobile EEG should facilitate better identification of commonalities and differences related to the development of expertise across sports and between individuals. While at this stage it is difficult to predict the full extent of applications for mobile EEG techniques in sport, it is clear that the development of a mobile cognition approach will help sports neuroscience to provide valuable insights into the relationship between psychological and physical aspects of real-world sporting performance.

Acknowledgement

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