4

Sport-Related EEG Activity

What Have We Learned from a Quarter-Century's Worth of Research?

Karla A. Kubitz

This chapter reviews the published literature examining sport-related EEG activity over the past quarter-century. Using several search engines to probe multiple databases with the key terms "EEG" and "sport", 13 reviews and 92 research studies were identified. Reviews and research studies were limited to those published in academic journals, in English, and between 1983 and 2016. The majority of the published reviews (Cheron et al., 2016; Cooke, 2013; Etnier & Gapin, 2014; Hatfield, Haufler, Hung, & Spalding, 2004; Hatfield & Kerick, 2007; Hatfield & Landers, 1983; Janelle & Hatfield, 2008; Lawton, Saarela, & Hatfield, 1998; Mancevska, Gligoroska, Todorovska, Dejanova, & Petrovska, 2016; Yarrow, Brown, & Krakauer, 2009) focused on the sport-related EEG research studies available at the time. Three of the published reviews (Gentili, Oh, Bradberry, Hatfield, & Contreras-Vidal, 2010; Mann & Janelle, 2012; Thompson, Steffert, Ros, Leach, & Gruzelier, 2008) focused technological considerations for sport-related EEG researchers. Significant conclusions for the most recent (i.e., those published within the past decade) of the published EEG research-focused reviews are described below.

Yarrow et al. (2009) reviewed the pre-2009 literature and drew two conclusions. First, they concluded that the literature supports the notion that experts demonstrate more efficient cortical processing. Second, they concluded that the literature supports a predictive relationship between sport-related EEG activity and performance.

Gentili et al. (2010) reviewed the pre-2010 literature and drew four conclusions. They concluded that the literature supported the existence of important relationships between sport-related EEG activity and performance. Second, they concluded that the literature supported the existence of differences in sport-related EEG activity between experts and novices. Third, they concluded that the literature supported the existence of learning effects. Fourth, they concluded that the literature supported the existence of specific locations and frequency bands of importance.

Cooke (2013) reviewed the pre-2013 literature and drew two main conclusions. First, the literature indicated differences in external information processing. Second, the literature indicated differences in verbal-analytic information processing.

Etnier and Gapin (2014) reviewed the pre-2014 literature and drew three conclusions. First that the sport-related EEG literature supported the existence of expert/novice differences in EEG activity. Second, that the literature supported the importance of left hemisphere activity. Third, Etnier and Gapin (2014) concluded that the sport-related EEG literature supported the importance of slow potential activity, specifically the contingent negative variation (CNV) waveform.

Mancevska et al. (2016) reviewed the pre-2016 literature and drew several important conclusions. First, they concluded that the literature supported a shift from left brain to right brain activity during sport performance. Second, they concluded that the literature supported the importance of reduced EEG coherence as a concomitant of optimal performance. Third, they concluded that the literature supported the importance of studying event-related potentials related to sport performance.

There were several similar conclusions in these reviews. Four of the reviews (Etnier & Gapin, 2014; Janelle & Hatfield, 2008; Lawton et al., 1998; Mancevska et al., 2016) concluded that the literature supported the existence of hemispheric differences in EEG activity during the pre-performance period. Three of the reviews (Hatfield et al., 2004; Janelle & Hatfield, 2008; Lawton et al., 1998) concluded that the literature supported the existence of decreased EEG activation during the pre-performance period. Two of the reviews (Etnier & Gapin, 2014; Gentili et al., 2010) concluded that the literature supported the existence of differences sport-related EEG activity between experts and novices. Two of the reviews (Etnier & Gapin, 2014; Mancevska et al., 2016) concluded that the literature supported the relevance of event-related potentials for understanding sport-related EEG activity.

Based on the aforementioned reviews of the sport-related EEG research studies (see Table A1 for methodological details on the sport-related EEG studies) over the past quarter-century, this chapter focuses on eight questions, including:

1. How does EEG activity change across the pre-performance period?
2. How is EEG activity different during good and poor performances?
3. How is EEG activity different in experts and novices?
4. How is EEG activity different in competitive athletes and non-athletes?
5. How is EEG activity different in disabled and non-disabled athletes?
6. How does practice/learning change EEG activity?
7. Is EEG activity during a sport task different from EEG activity during other tasks (e.g., balancing on a stabilometer)?
8. Is sport-related EEG activity changed by socio-environmental manipulations (e.g., adding competition)?

How Does EEG Activity Change across the Pre-Performance Period?

Several early (pre-2001) studies recorded theta and/or alpha activity (i.e., using power, ERD/ERS, and/or asymmetry metrics) during the pre-performance period. For example, Hatfield, Landers, and Ray (1984, Study 1) used a within-subject design to examine shooting-related EEG activity. Participants were 17 elite-level shooters who performed an air rifle shooting task. Hatfield et al. recorded spontaneous EEG activity, specifically alpha activity before shooting. They found that alpha power at T3 increased and alpha power at T4 remained constant across time during the pre-performance period. In like manner, Hatfield, Landers, and Ray (1987) used a within-subject design to examine shooting-related EEG activity. Participants were 15 expert marksmen who performed self-paced 40 shots to a target. Hatfield et al. recorded spontaneous EEG activity, specifically theta, alpha, and beta activity, before shooting. In addition, they recorded heart rate. They found no significant differences in heart rate or alpha activity across time during the pre-performance period. However, there was a trend for heart rate and for alpha activity (at T3) to increase across this period. Continuing, the focus on shooting, Janelle et al. (2000) used a between-subject design to examine shooting-related EEG activity. Participants were 12 expert shooters and 13 non-expert shooters who performed 40 shots in a standing position using the Noptel Shooter Training system. Janelle et al. recorded spontaneous EEG activity, specifically alpha activity. They also recorded visual point of gaze (as an index of Quiet Eye duration). The results revealed that experts had higher performance scores and longer quiet eye periods than novices. Both experts and novices exhibited increased left hemisphere alpha power and decreased right hemisphere alpha power during shooting. Focusing on a different sport, Salazar et al. (1990) used a multi-factorial design to examine archery-related EEG activity. Participants were 13 male and 15 female archers who performed four tasks, including shooting with normal bow; shooting with light bow; bow drawing without aiming; and aiming without bow drawing. Salazar et al. recorded spontaneous EEG activity, specifically 5–31 Hz activity. The results indicated that power at 10 and 12 Hz (i.e., T3 alpha activity) increased across the pre-performance period. However, power at T4 remained constant across the same period. Continuing this line of inquiry, Crews and Landers (1993) used a within-subject design to examine golf-related EEG activity. Participants were 34 highly skilled golfers who performed a putting task. Crews and Landers recorded both spontaneous and event-related EEG activity, including theta, alpha, beta1, beta2, and 40 Hz activity. They found that left hemisphere alpha power increased and right hemisphere alpha power decreased across time during the pre-performance period.

Numerous recent studies also recorded theta and/or alpha activity (i.e., using power, ERD/ERS, and/or asymmetry metrics) during the pre-performance period. The majority focused on alpha activity. For example, Loze, Collins, and Holmes (2001) used a within-subject design to examine shooting-related EEG activity. Participants were six expert air-pistol shooters who performed a shooting task. Loze et al. recorded spontaneous EEG activity, specifically alpha activity. The results revealed that there was a lower level of alpha power at T4 than at T3 (i.e., asymmetry was negative) during the pre-performance period. In like manner, Kerick, McDowell, and Hung (2001) used a within-subject design to examine shooting-related EEG activity. Participants were eight skilled marksmen who performed shooting, postural control, and movement control tasks. Kerick et al. recorded event-related EEG activity, specifically alpha ERD. They reported that high alpha power (at T3) increased across the pre-performance period and that there were no changes during this period at T4, C3, or C4. Similarly, Holmes, Collins, and Calmels (2006) used a within-subject design to compare EEG activity across the pre-performance period. Participants were six expert shooters who performed 40 shots (using the SCATT Shooter Training system) and three observation tasks. Holmes et al. recorded event-related EEG activity, specifically alpha ERD. The results showed that alpha desynchronization (in the right hemisphere) increased (i.e., alpha power decreased) across the pre-performance period in the shooting condition. Focusing on archery, Twigg, Sigurnjak, Southall, and Shenfield (2014) used a within-subject design to examine shooting-related EEG activity. Participants were two experienced archers who shot 12 arrows each. Twigg et al. recorded spontaneous EEG activity, specifically 1–30 Hz activity. They reported that alpha activity increased across the pre-performance period. Although most of these studies focused on alpha activity, there was one study that focused on theta activity. Specifically, Doppelmayr, Finkenzeller, and Sauseng (2008) used a between-subject design to examine shooting-related EEG activity. Participants were eight expert shooters and 10 novice shooters who performed 10 blocks of five shots each. Doppelmayr et al. recorded spontaneous EEG activity, specifically frontal midline theta activity. Furthermore, they performed source localization using the LORETA algorithm. The results indicated that frontal midline theta (at Fz) increased across the pre-performance period.

A small group of studies recorded other EEG measures, including higher frequency EEG activity, EEG coherence, event-related potentials, or self-organizing neural networks during the pre-performance period. As mentioned previously, Janelle et al. (2000) used a between-subject design to examine shooting-related EEG activity. In addition to the findings described earlier in this section, they also reported that experts had higher performance scores and longer quiet eye periods than novices. Moreover, both experts and novices exhibited increased left hemisphere beta power and decreased right hemisphere beta power during shooting. As mentioned previously, Twigg et al. (2014) used a within-subject design to examine shooting-related EEG activity. In addition to the findings described earlier in this section, they also reported that beta activity decreased across the pre-performance period. Focusing on coherence, Wu, Lo, Lin, Shih, and Hung (2007) used a within-subject design to examine sport-related EEG activity. Participants were 12 highly skilled basketball players who shot 50 baskets. Wu et al. recorded spontaneous

EEG activity, specifically low alpha, high alpha, and low beta coherence. The results indicated that high alpha and low beta coherence decreased across the pre-performance period. Focusing on event-related potentials, Konttinen and Lyytinen (1992) used a mixed-model design to examine sport-related EEG activity. Participants were three skilled marksmen and three novice shooters who performed a simulated rifle shooting task. Konttinen and Lyytinen recorded event-related EEG activity, specifically slow potential waveforms. Additionally, they recorded heart rate and respiration. The results indicated that, for all shooters, heart rate decreased and slow potential negativity (at C3 and C4) increased across the pre-performance period. Focusing on self-organizing neural networks, Stikic et al. (2014, Study 1) used a within-subject design to examine shooting-related EEG activity. Participants were 51 adult volunteers (i.e., without any marksmanship training) who performed a simulated shooting task using the Virtual Battle Space2 Tactical Warfare Simulator. Stikic et al. recorded spontaneous EEG activity, specifically self-organizing neural networks. In particular, they used the B-Alert model to classify cognitive states according to engagement and workload. The results showed that a neural network successfully indexed engagement and workload during a simulated shooting task. The nodes that were activated most often included nodes 8, 6, and 11. Node 8 represented low EEG-engagement, node 6 represented high EEG-engagement, and node 11 represented both EEG-engagement and EEG workload.

In summary, there were 15 studies that examined changes in sport-related EEG activity across the pre-performance period. Most (n=10) of these examined changes in alpha activity across the pre-performance period. There seems to be a consensus that alpha activity (particularly in the left hemisphere) increases across the pre-performance period. All but one of the studies examining alpha activity reported increased left hemisphere alpha activity across the pre-performance period. The exception, Holmes et al. (2006) reported increased right hemisphere alpha ERD (i.e., decreased alpha activity) across the pre-performance period. Only six studies examined measures other than alpha activity, including theta (n=1), beta (n=2), EEG coherence (n=1), slow potentials (n=1), and self-organizing neural networks (n=1). Consequently, it was impossible to draw conclusions regarding changes in any of the other EEG measures (i.e., other than alpha activity) across the pre-performance period.

How Is EEG Activity Different During Good and Poor Performances?

Quite a few studies recorded theta activity (i.e., using power, ERD/ERS, and/or asymmetry metrics) during good and poor performances. Among them, Salazar et al. (1990) used a multi-factorial design to compare EEG activity during good and poor performances. Participants were 13 male and 15 female archers who performed four tasks, including shooting with normal bow; shooting with light bow; bow drawing without aiming; and aiming without bow drawing. Salazar et al. recorded spontaneous EEG activity, specifically 5–31 Hz activity. The results showed that 7 Hz theta power (i.e., at T3) was lower during good performance than during poor performance. Along the same lines, Kao, Huang, and Hung (2013) used a within-subject design to compare EEG activity during good and poor performances. Participants were 18 skilled golfers who performed 100 putts. Putts were divided into 15 best and 15 worst outcomes. Kao et al. (2013) recorded spontaneous EEG activity, specifically frontal midline theta activity. The results indicated that there was a lower level of frontal midline theta activity (at Fz, Cz, and Pz) in the best relative to the worst shots. Similarly, Chuang, Huang, and Hung (2013) used a within-subject design to compare EEG activity during good and poor performance. Participants were 15 skilled basketball players who performed basketball free throw shots. Chuang et al. recorded spontaneous EEG activity, specifically low theta and high theta band activity. They reported that theta1 power (at Fz) and theta2 power (at Fz and F4) remained stable during the pre-performance period for successful shots. In contrast, theta power was unstable for unsuccessful shots. Likewise, Dyke et al. (2014) used a within-subject design to compare EEG activity during good and poor performances.

Participants were 13 novice golfers who performed 30 putts. Putts were divided into five most and five least accurate. Dyke et al. recorded spontaneous EEG activity, specifically theta, low alpha, high alpha, low beta, high beta, and gamma activity. They reported higher levels of theta activity (in the left temporal area) before the more accurate putts. Taking a different, model-building approach, di Fronso et al. (2016) used a within-subject design to compare EEG activity during good and poor performances. The study tested the predictions of the 'multi-action plan' (MAP) model. The MAP model predicted specific within-subject differences in EEG activity (and perceived control) between four types of shots, including Type I/Efficient shots, Type II/Effortful shots, Type III/Impaired shots, and Type IV/Inefficient shots. A single elite air pistol shooter performed 40 self-paced shots. Di Fronso et al. recorded event-related EEG activity, specifically theta, low alpha, and high alpha event-related synchrony. Types I and II had the best shooting scores. In addition, consistent with the MAP model, Type I/Efficient shots were characterized by increased theta synchrony (i.e., more theta activity) and Type II/Effortful shots were characterized by decreased theta synchrony (i.e., less theta activity). Also testing the MAP model, Bertollo et al. (2016) used a within-subject design to compare EEG activity during good and poor performances. Participants were 10 elite shooters who performed 120 shots. Bertollo et al. recorded event-related EEG activity, specifically theta, low alpha, and high alpha event-related synchrony. The results, once again, supported the MAP model. That is, Type I/Efficient shots were characterized by increased theta synchrony (i.e., more theta activity). Type II/Effortful and Type III/Impaired shots were characterized by decreased theta synchrony (i.e., less theta activity).

Several early (pre-2001) studies recorded alpha activity (i.e., using power, ERD/ERS, and/or asymmetry metrics) during good and poor performances. Among them, Bird (1987) used a within-subject design to compare EEG activity during good and poor performances. A single elite marksman performed a shooting task. Bird recorded spontaneous EEG activity, specifically EEG peak frequency. The results indicated that the average frequency was lower (about 12–14 Hz) in good than in poor shots (about 14–16 Hz). As mentioned previously, Salazar et al. (1990) used a multi-factorial design to compare EEG activity during good and poor performances. In addition to the findings described earlier in this section, they also reported that 12 Hz alpha power (i.e., at T3) was lower during good performance than during poor performance. Continuing the focus on shooting, Hillman, Apparies, Janelle, and Hatfield (2000) used a within-subject design to compare EEG activity during good and poor performance. Participants were seven expert shooters who performed a simulated rifle shooting task. Hillman et al. recorded spontaneous EEG activity, specifically alpha and beta activity. They found that good performances (i.e., executed shots) were accompanied by lower alpha power than poor performances (i.e., rejected shots).

Numerous recent studies recorded alpha activity (i.e., using power, ERD/ERS, and/or asymmetry metrics) during good and poor performances. Among these, Loze et al. (2001) used a within-subject design to compare EEG activity during good and poor performances. Participants were six expert air-pistol shooters who performed a shooting task. Loze et al. recorded spontaneous EEG activity, specifically alpha activity and found differences in EEG activity between good and bad shots. Alpha power (at Oz) was higher before good shots and lower before bad shots. Similarly, Bablioni et al. (2008) used a within-subject design to compare EEG activity during good and poor performances. Participants were 12 expert golfers who performed 10 blocks of 10 putts each (while standing on a balance platform) using a putting green simulator. Bablioni et al. recorded spontaneous EEG activity, specifically alpha and beta activity. Furthermore, they performed source localization using the Laplacian transformation algorithm and measured body sway. The results showed that the amplitude of high frequency alpha power (at Cz) was lower in the successful than in the unsuccessful putts. In addition, alpha power and performance were positively related. That is, putts were closer to the hole when there were larger decreases in alpha power and farther away from the hole when there were smaller decreases in alpha power. Likewise, Cooke et al. (2014) used a mixed-model design to compare sport-related EEG activity between good and poor performances. Participants were 10 expert golfers and 10 novice golfers who performed 60 putts. Cooke et al. recorded spontaneous EEG activity, specifically theta, low alpha, high alpha, and beta activity. In addition, they recorded number of putts holed, self-reported pressure, movement kinematics, heart rate, and EMG activity. The results indicated that experts had less low alpha power and less high alpha power (at frontal and central sites) for holed putts than for missed putts. Focusing on ERD/ERS, Del Percio, Bablioni, Bertollo et al. (2009) used a mixed-model design to compare EEG activity across good and poor performances. Participants were 18 expert shooters and 10 non-athletes who performed 120 shots. Del Percio, Bablioni, Bertollo et al. recorded event-related EEG activity, specifically low alpha and high alpha ERD. They performed source localization using the Laplacian transformation algorithm. The results revealed that high-frequency alpha ERD was less (i.e., alpha power was higher) for high score shots than for low score shots. As mentioned previously, Bertollo et al. (2016) used a within-subject design to compare EEG activity during good and poor performances. In addition to the findings described earlier in this section, they also reported that Type I/Efficient shots were characterized by increased low alpha synchrony (i.e., more alpha activity). Moreover, Type II/Effortful and Type III/Impaired shots were characterized by decreased low alpha synchrony (i.e., less alpha activity).

A few studies recorded beta and/or gamma activity during good and poor performances. Each of these studies have been mentioned previously. Among these, Salazar et al. (1990) used a multi-factorial design to compare EEG activity during good and poor performances. In addition to the findings described earlier in this section, they also reported that beta power (i.e., 28 Hz power at T3) was lower during good performance than during poor performance. Similarly, Hillman et al. (2000) used a within-subject design to compare EEG activity during good and poor performance. In addition to the findings described earlier in this section, they also reported that good performances (i.e., executed shots) were accompanied by lower beta power than poor performances (i.e., rejected shots). Likewise, Dyke et al. (2014) used a within-subject design to compare EEG activity during good and poor performances. In addition to the findings described earlier in this section, they also reported higher levels of low beta activity (in the left temporal area) before the more accurate putts.

Several recent studies recorded EEG coherence during good and poor performances. Among them, Wu et al. (2007) used a within-subject design to compare EEG activity during good and poor performances. Participants were 12 highly skilled basketball players who shot 50 baskets. Wu et al. recorded spontaneous EEG activity, specifically low alpha, high alpha, and low beta coherence. They found coherence was lower across all frequency bands for good shots than for poor shots. Furthermore, Gallicchio, Cooke, and Ring (2015) used a mixed-model design to compare sport-related EEG activity between experts and novices. Participants were 10 expert golfers and 10 novice golfers who performed 60 putts. Gallicchio et al. recorded spontaneous EEG activity, specifically left and right hemisphere alpha coherence. They found less left hemisphere high alpha coherence for successful than for unsuccessful putts. There were no differences in right hemisphere high alpha coherence between successful and unsuccessful putts. Likewise, Bablioni et al. (2011) used a within-subject design to compare EEG activity during good and poor performances. Participants were 12 expert golfers who performed 100 self-paced putts using a golf green simulator. Bablioni et al. recorded spontaneous EEG activity, specifically low alpha and high alpha coherence. Furthermore, they performed source localization using the Laplacian transformation algorithm. They reported that intra-hemispheric coherence (in parietal and frontal sites) was higher during successful putts than during unsuccessful putts. As mentioned previously, Dyke et al. (2014) used a within-subject design to compare EEG activity during good and poor performances. In addition to the findings described earlier in this section, they also reported no significant differences in EEG coherence between the more and the less accurate putts.

Several studies recorded event-related potentials during good and poor performances. Among those, Konttinen and Lyytinen (1992) used a mixed-model design to compare EEG activity across good and poor performances. Participants were three skilled marksmen and three novice shooters who performed a simulated rifle shooting task. Konttinen and Lyytinen recorded event-related EEG activity, specifically slow potential waveforms. In addition, they recorded heart rate and respiration. They reported that the experts' best shots were accompanied by less negativity (at Fz) than their worst shots. Similarly, Konttinen, Lyytinen, and Konttinen (1995) used a within-subject design to compare EEG activity during good and poor performances. Participants were six elite marksmen and six pre-elite marksmen who performed a simulated rifle shooting task. Konttinen et al. recorded event-related EEG activity, specifically slow potential waveforms. They found that there was less slow potential negativity/more frontal slow potential positivity during good versus poor performances. Extending these findings, Konttinen and Lyytinen (1993a) used a within-subject design to compare EEG activity during good and poor performances. Participants were 12 expert shooters who performed a simulated rifle shooting task. Konttinen and Lyytinen recorded event-related EEG activity, specifically slow potential waveforms. They also recorded heart rate and respiration. They found individual differences in slow potential waveforms during shooting. There was a unique slow potential profile (i.e., a certain amount of negativity and/or positivity) for each shooter, a profile that differed across their good and poor performances.

In summary, there were 23 studies that examined differences in sport-related EEG activity between good and poor performances. Most (n=13) of these examined changes in theta and/or alpha activity between good and poor performances. A few studies examined changes in beta activity (n=3), EEG coherence (n=4), or slow potentials (n=3). Across these studies, two points of agreement emerged. First, there seems to be a consensus that beta activity is lower in good performances than in poor performances. All three of the studies reviewed reported that beta activity was lower in good performances than in poor performances. Second, there seems to be a consensus that slow potential shifts are less negative in good performances than in poor performances. All but one of the studies reviewed reported that slow potential shifts were less negative in good performances than in poor performances. The exception (Konttinen & Lyytinen, 1993a) reported individual differences in slow potentials between good and poor performances. Finally, the findings were mixed regarding differences in theta activity, alpha activity, and EEG coherence between good and poor performances.

How Is EEG Activity Different in Experts and Novices?

A small group of studies recorded theta activity (i.e., using power, ERD/ERS, and/or asymmetry metrics) in expert and novice performers. Among those, Haufler, Spalding, Maria, and Hatfield (2000) used a mixed-model design to compare sport-related EEG activity between experts and novices. Participants were 15 elite shooters and 21 novice shooters who performed simulated a simulated rifle shooting task. Haufler et al. recorded spontaneous EEG activity, specifically theta, low alpha, high alpha, beta, and gamma activity. They reported that experts performed better on the shooting task than novices. Moreover, experts had more left (and right) hemisphere theta activity during shooting than novices. Continuing the focus on shooters, Doppelmayr et al. (2008) used a between-subject design to compare shooting-related EEG activity in experts and novices. Participants were eight expert shooters and 10 novice shooters who performed 10 blocks of five shots each. Doppelmayr et al. recorded spontaneous EEG activity, specifically frontal midline theta activity. They also performed source localization using the LORETA algorithm. They reported that frontal midline theta activity (at Fz) was higher for experts than for novices (during last 3s before the shot). Focusing on golfers, Baumeister, Reinecke, Liesen, and Weiss (2008) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were nine experienced golfers and nine novice golfers who performed five blocks of 10 putts each on an indoor carpet putting green. Baumeister et al. recorded spontaneous EEG activity, specifically theta, alpha1, alpha2, beta1, and beta2 activity and EEG asymmetry. In addition, they measured anxiety (using the State-Trait Anxiety Inventory) and stress (using a visual analog scale). The results revealed that experts performed better than novices. Performance differences were accompanied by EEG differences. Experts had higher theta (at Fz and Pz) than novices. Continuing the focus on golfers, Cooke et al. (2014) used a mixed-model design to compare sport-related EEG activity between experts and novices. Participants were 10 expert golfers and 10 novice golfers who performed 60 putts. Cooke et al. recorded spontaneous EEG activity, specifically theta, low alpha, high alpha, and beta activity. In addition, they recorded number of putts holed, self-reported pressure, movement kinematics, heart rate, and EMG activity. The results indicated that experts had less theta power during the pre-putt period than novices.

Another small group of studies recorded alpha activity (i.e., using power, ERD/ERS, and/or asymmetry metrics) in expert and novice performers. Each of these studies has been mentioned previously. Among them, Haufler et al. (2000) used a mixed-model design to compare sport-related EEG activity between experts and novices. In addition to the findings mentioned earlier in this section, they also reported that experts performed better on the shooting task than novices. Moreover, experts had more left hemisphere low alpha activity and more left hemisphere high alpha activity during shooting than novices. Similarly, Baumeister et al. (2008) used a between-subject design to compare sport-related EEG activity in experts and novices. In addition to the findings described earlier in this section, experts had higher alpha1 (at Pz), and alpha2 (at Pz) than novices. Likewise, Cooke et al. (2014) used a mixed-model design to compare sport-related EEG activity between experts and novices. In addition to the findings described earlier in this chapter, they also reported that experts had more high alpha power during the pre-putt period than novices. Continuing this line of inquiry, Janelle et al. (2000) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were 12 expert shooters and 13 non-expert shooters who performed 40 shots in a standing position using the Noptel Shooter Training system. Janelle et al. recorded spontaneous EEG activity, specifically alpha activity. Additionally, they recorded visual point of gaze (as an index of Quiet Eye duration). They found that experts had longer quiet eye periods and better performance than novices. However, there were no between-group differences in alpha activity. Likewise, Taliep and John (2014) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were eight skilled and 10 less skilled cricket batsmen. The cricket batsmen watched 24 bowling deliveries and decided whether they were in-swinger or out-swinger deliveries. Taliep et al. recorded event-related EEG activity, specifically alpha ERD. The results indicated that expert batsmen showed more alpha synchronization (i.e., more alpha activity) than novices during the pre-performance period. These differences were statistically significant from −1500s to −250s before ball release.

A few studies recorded beta and/or gamma activity in expert and novice performers. Each of these studies has been mentioned previously. Among these, Haufler et al. (2000) used a mixed-model design to compare sport-related EEG activity between experts and novices. In addition to the findings mentioned earlier in this section, they also reported that experts performed better on the shooting task than novices. Moreover, experts had less left and right hemisphere (except for T3) beta activity and less left and right hemisphere gamma activity during shooting than novices. Similarly, Janelle et al. (2000) used a between-subject design to compare sport-related EEG activity in experts and novices. In addition to the findings described earlier in this section, they also reported that there were no between-group differences in beta activity. Likewise, Cooke et al. (2014) used a mixed-model design to compare sport-related EEG activity between experts and novices. In addition to the findings described earlier in this section, they also reported that experts had more beta power during the pre-putt period than novices.

In addition, a few studies recorded SMR activity in expert and novice performers. For example, Wolf et al. (2014) used a between-subject design to compare sport-related EEG activity in different levels of expertise. Participants were 14 expert table tennis players, 15 amateur table tennis players, and 15 young elite table tennis players who watched 40 videos of table tennis strokes. Participants were asked to imagine themselves responding to the strokes. Wolf et al. recorded event-related EEG activity, specifically sensorimotor ERD. They reported that SMR desynchronization was greater (i.e., there was less SMR activity) in elite athletes (over the motor cortex) than in amateur athletes. In addition, Cheng et al. (2015) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were 14 expert dart throwers and 11 novice dart throwers who performed 60 self-paced dart throws. Cheng et al. recorded spontaneous EEG activity, specifically sensorimotor ERD. In addition, they recorded EMG activity from forearm flexor muscles. They found that experts had higher SMR activity and higher beta1 activity during the pre-performance period than novices.

Numerous studies recorded EEG coherence in expert and novice performers. Among those, Deeny, Hillman, Janelle, and Hatfield (2003) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were 10 expert shooters and nine less skilled shooters who completed a shooting task. Deeny et al. recorded spontaneous EEG activity, specifically low alpha, high alpha, and beta coherence. The results showed that experts had lower low alpha (between T3 and Fz), high alpha (between all left hemisphere sites and Fz), and low beta coherence (between T3 and Fz) than novices. Extending the results of the earlier study, Deeny, Haufler, Saffer, and Hatfield (2009) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were 15 expert shooters and 21 novice shooters who performed 40 self-paced shots using the Noptel Shooter Training System. Deeny et al. recorded spontaneous EEG activity, specifically theta, low alpha, high alpha, low beta, high beta, and gamma coherence. Additionally, they recorded variability in aiming point. They found difference in shooting scores between experts and novices. These differences were accompanied by lower EEG coherence (most evident in the right hemisphere) in experts than in novices. In addition, EEG coherence (in low alpha at F4-P4, F4-O2, F3-P3, and F3-O1) was positively correlated with movement variability during aiming. Additionally, Gallicchio et al. (2015) used a mixed-model design to compare sport-related EEG activity between experts and novices. Participants were 10 expert golfers and 10 novice golfers who performed 60 putts. Gallicchio et al. recorded spontaneous EEG activity, specifically left and right hemisphere alpha coherence. They reported that there was less left hemisphere high alpha coherence (between T7 and Fz) during the pre-performance period in experts than in novices. However, there were no differences in right hemisphere high alpha coherence between experts and novices. Continuing this line of inquiry, Harung (2011) used a between-subject design to compare sport-related EEG activity in different levels of expertise. Participants were 33 Olympic/world class and 33 competitive athletes who performed two paired reaction time tasks (i.e., tasks that included a warning stimulus followed by an imperative stimulus). Harung recorded spontaneous EEG activity, specifically 6–40 Hz EEG coherence. The results showed that 6–40 Hz EEG coherence were higher in world class than in average athletes. Taking a slightly different approach, Wolf, Brölz, Keune, and Wesa (2015) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were 14 expert table tennis players and 15 amateur table tennis players who watched 40 videos of table tennis strokes and imagined themselves responding to the strokes. Wolf et al. recorded spontaneous EEG activity, specifically theta coherence. The results indicated that experts had higher T4-Fz theta coherence than amateurs.

A few studies recorded event-related potentials in expert and novice performers. Among these, Radlo, Janelle, Barba, and Frehlich (2001) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were 10 advanced baseball players and 10 intermediate-level baseball players who completed a baseball pitch discrimination task. Radlo et al. recorded event-related EEG activity, specifically the P300 event-related potential. Additionally, they recorded reaction times. The results revealed that advanced players had shorter reaction times and more correct responses (when judging baseball pitches) than intermediate-level players. This was accompanied by differences in the P300 event-related potential waveform. Advanced players had longer P300 latencies and smaller P300 amplitudes than intermediate-level players. In addition, Hack, Memmert, and Rupp (2009) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were 10 experienced basketball referees and 10 novice basketball referees who judged pictures of basketball game situations varying on the presence/absence of a foul. Hack et al. recorded event-related EEG activity, specifically the N1 and P300 waveforms. They found that the event-related potentials were different for experienced and novice referees. Experienced referees had higher N1 and P3 amplitudes relative to novice referees. In addition, experienced referees had shorter P3 latencies (at Pz) than novice referees. However, there were no differences in foul judgment accuracy between the two groups.

A few early studies recorded slow potentials in expert and novice performers. Among them, Fattapposta et al. (1996) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were eight elite pentathletes and eight novice pentathletes who completed the Skilled Performance Task (i.e., an interactive bi-manual motor-perceptual task). Fattapposta et al. recorded event-related EEG activity, specifically movement-related cortical potentials. In particular, they focused on the Bereitschaftspotential and skilled performance positivity waveforms. They reported better performance in the expert than in the novices. This was accompanied by smaller Bereitschaftspotential and larger skilled performance positivity waveforms in experts than in novices. Similarly, Konttinen, Lyytinen, and Viitasalo (1998) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were six elite marksmen and six pre-elite marksmen who performed a simulated rifle shooting task. Konttinen et al. recorded event-related EEG activity, specifically slow potentials. The results of the study were that elite and pre-elite shooters used different rifle-holding strategies and had differences in slow potential activity. For elite shooters, frontal (Fz) slow potential positivity was associated with decreased rifle stability. For pre-elite shooters, frontal (Fz) slow potential positivity was associated with increased rifle stability. Continuing this line of inquiry, Konttinen, Lyytinen, and Era (1999) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were six elite marksmen and six pre-elite marksmen who performed a simulated rifle shooting task. Konttinen et al. recorded event-related EEG activity, specifically slow potentials. They also recorded body sway during shooting. The results of the study were that there was were different relationships in the elite and the pre-elite shooters between slow potentials and body sway. For elite shooters, decreased frontal slow potential positivity was associated with greater stability. For pre-elite shooters, decreased central (C4) slow potential Negativity was associated with greater stability. Similarly, Konttinen, Landers, and Lyytinen (2000) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were six elite marksmen and six pre-elite marksmen who performed a simulated rifle shooting task. Konttinen et al. recorded event-related EEG activity, specifically slow potentials. The results of the study were that pre-trigger slow potentials (at Fz) were more positive among elite shooters than among pre-elite shooters.

Several recent studies also recorded slow potentials in expert and novice performers. Among them, Mann, Coombes, Mousseau, and Janelle (2011) used a between-subjects design to compare sport-related EEG activity in experts and novices. Participants were 10 expert golfers and 10 near-expert golfers who performed two blocks of 45 putts each. Mann et al. recorded event-related EEG activity, specifically movement-related cortical potentials (i.e., the Bereitschaftspotential). In addition, Mann et al. recorded the Quiet Eye duration and EMG activity from right forearm extensor muscles. They reported that experts made more putts and had a longer quiet eye period than near-experts. This was accompanied by greater negativity in the Bereitschaftspotentials of the experts than of the novices. This difference was clear at C4 for the early and late components and at P4 for the early component only. Moreover, there were no expert/near-expert differences for any of the C3, P3, or Cz components. Likewise, Nakamoto and Mori (2012) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were seven expert baseball players and seven novice baseball players who performed an anticipation timing (Go/No-go) reaction time task in two conditions, timing unchanged and timing changed. Nakamoto et al. recorded event-related EEG activity, specifically movement-related cortical potentials. They focused on the contingent negative variation (CNV) waveform. They found that experts made fewer timing errors during the anticipation timing task. In addition, experts had shorter latencies for the CNV waveform and increased amplitudes for the N200 and P300 waveforms. As mentioned previously, Harung (2011) used a between-subject design to compare sport-related EEG activity in different levels of expertise. Participants were 33 Olympic/world class and 33 competitive athletes who performed two paired reaction time tasks (i.e., tasks that included a warning stimulus followed by an imperative stimulus). Harung recorded slow potential waveforms (i.e., the CNV waveform). The results showed that the amplitudes of the late CNV waveform (in frontal and central areas) were higher in world class than in average athletes. Along the same line, Hung, Spalding, Maria, and Hatfield (2004) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were 15 highly skilled table tennis players and 15 non-athletic college students who completed a cued reaction time task (i.e., Posner's cued attention task). Hung et al. recorded event-related EEG activity, specifically slow potentials. In particular, they focused on lateralized readiness potentials, which reflect cortical preparation for cued hand movement. The results indicated that skilled table tennis players had faster reaction times to both correctly and incorrectly cued stimuli than novices. They also had larger lateralized readiness potentials than novices.

Last, two studies recorded different EEG metrics in expert and novice performers. First, Del Percio, Brancucci et al. (2007) used a multi-factorial design to compare sport-related EEG in experts and novices. Participants were 17 elite karate athletes, 14 amateur karate athletes, and 15 non-athletes who observed 180 pictures different karate attacks and decided whether the attacks were right/left side attacks. Del Percio et al. recorded event-related EEG activity, specifically visual evoked potentials. The results revealed that the elite karate athletes had a smaller amplitude visual evoked potential waveform (at 300–450 ms) for the karate than for the fencing attacks. Second, Hung, Haufler, Lo, Mayer-Kress, and Hatfield (2008) used a between-subject design to compare sport-related EEG activity between experts and novices. Participants were 15 expert shooters and 21 novice shooters who performed 40 shots (with a 5s aiming period) in a standing position. Hung et al. recorded spontaneous EEG activity, specifically EEG dimensionality (i.e., D2). D2 is an "estimate of the number of active cell assemblies that produce the [EEG] signal through their independent oscillations" (Hung et al., 2008, p. 753). D2 was calculated using the Dataplore software. The results of the study were that experts showed higher performance accuracy and lower D2 than novices. In addition, shooting performance and D2 were negatively correlated (in experts). That is, better shooting performance was associated with a lower level of D2. Novices showed the opposite relationship, a positive correlation between shooting performance and D2. Third, Stikic et al. (2014, Study 2) used a within-subject design to examine golfing-related EEG activity. Participants were 11 experienced golfers and 11 novice golfers who performed 10 sessions of 10 putts each. They recorded spontaneous EEG activity, specifically self-organizing neural networks (using the B-Alert model generated in Study 1). The results of Study 2 showed EEG-engagement and EEG workload were higher than average during the pre-performance period and decreased afterwards. The results of Study 2 showed that node 11 (both EEG engagement and EEG workload) and node 6 (EEG-engagement) were activated most often during golfing. That is, golfing activated two of the same nodes (i.e., 6 and 11) that shooting did (in Study 1) but did not activate node 8 (low EEG-engagement).

In summary, there were 32 studies that examined differences in sport-related EEG activity between experts and novices. The majority of these examined differences in alpha activity (n=5), EEG coherence (n=5), or slow potentials (n=8) between experts and novices. A few studies examined differences in theta activity (n=4), beta activity (n=3), SMR activity (n=2), event-related potentials (n=2), evoked potentials (n=1), EEG dimensionality (n=1), and self-organizing neural networks (n=1). Across these studies, two points of agreement emerged. First, there seems to be a consensus that theta activity and alpha activity are higher in experts than in novices. Three out of the four studies reviewed reported that theta activity was higher in experts than in novices. The exception (Andrew Cooke et al., 2014) reported lower theta in experts than in novices. Four out of the five studies reviewed reported that alpha activity was higher in experts than in novices. The exception (Janelle et al., 2000) reported no significant differences in alpha activity between experts and novices. Second, there seems to be a consensus that EEG coherence is lower in experts than in novices. Three out of the five studies reviewed reported that EEG coherence was lower in experts than in novices. The exceptions (Harung, 2011; Wolf et al., 2015) reported that EEG coherence was higher in experts than in novices. Finally, the findings were mixed regarding differences in beta activity, SMR activity, and event-related potentials between experts and novices.

How Is EEG Activity Different in Competitive Athletes and Non-athletes?

A small group of studies recorded theta activity (i.e., using power, ERD/ERS, and/or asymmetry metrics) in competitive athletes and non-athletes. Among them, Ziółkowski et al. (2014) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were 36 amateur boxers and 52 college student volunteers who completed three one-minute periods, including maintaining eyes open, maintaining eyes closed, and maintaining visual focus. Ziółkowski et al. recorded spontaneous EEG activity, specifically delta, theta, alpha, SMR, beta, and high beta activity. They found that there was less theta activity in competitive athletes than in non-athletes. Similarly, Wang et al. (2015) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were 12 experienced badminton players and 13 non-athletes who performed visuospatial attention and working memory tasks. Wang et al. recorded spontaneous EEG activity, specifically theta, alpha, and beta activity. The results showed that athletes (i.e., badminton players) had faster reaction times and were more accurate than non-athletes. This performance difference was accompanied by increased theta activity in competitive athletes relative to non-athletes. Likewise, Ermutlu, Yücesir, Eskikurt, Temel, and İşoğlu-Alkaç (2015) used a between-subject design to examine EEG activity different athletes. Participants were 12 dancers, 12 fast ball sport athletes, and 12 non-athletes who completed a five-minute period of 'awake' relaxation. Ermutlu et al. recorded spontaneous EEG activity, specifically delta, theta, alpha, and beta activity. The results indicated that ball players had a higher level of slower frequency EEG (i.e., both theta and delta activity) than did dancers or non-athletes. In addition, Luchsinger, Sandbakk, Schubert, Ettema, and Baumeister (2016) used a mixed-model design to compare sport-related EEG activity between athletes and non-athletes. Participants were nine biathletes and eight non-athletes who performed 100 shots using the SCATT Shooter Training system. Luchsinger et al. recorded spontaneous EEG activity, specifically frontal theta activity. In addition, they measured perceived exertion (using a Borg scale) and self-reported concentration (using a visual analog scale). They reported that biathletes had more frontal theta activity during shooting than did non-athletes.

Another small group of studies recorded alpha activity (i.e., using power, ERD/ERS, and/or asymmetry metrics) in competitive athletes and non-athletes. Leading off this group of studies, Del Percio, Bablioni, Bertollo et al. (2009) used a mixed-model design to compare sport-related EEG activity between athletes and non-athletes. Participants were 18 expert shooters and 10 non-athletes who performed 120 shots. Del Percio, Bablioni, Bertollo et al. recorded event-related EEG activity, specifically low alpha and high alpha ERD. They performed source localization using the Laplacian transformation algorithm. The results revealed that low- and high-frequency alpha ERD was less in shooters than in non-athletes. Similarly, Del Percio, Bablioni, Marzano et al. (2009) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were 10 elite karate athletes, 10 elite fencing athletes, and 12 non-athletes who performed an eyes-open balancing task (i.e., balancing on two feet and balancing on one foot) on a stabilometer. Del Percio, Bablioni, Marzano et al. recorded event-related EEG activity, specifically alpha ERD. They performed source localization using the Laplacian transformation algorithm and also recorded body sway during balancing. They reported that 8–10 Hz alpha ERD was lower (in left and right central as well as mid and right parietal areas) during balancing in competitive athletes than in non-athletes. In addition, 10–12 Hz alpha ERD (in right frontal, left and right central, and mid parietal areas) was lower during balancing in competitive athletes than in non-athletes. Extending this line of research, Del Percio et al. (2010) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were 10 elite karate athletes and 12 non-athletes who performed wrist extensions of the right and left hands. Del Percio et al. recorded event-related EEG activity, specifically low alpha and high alpha ERD. They performed source localization using the LORETA algorithm. The results indicated that 8–10 Hz and 10–12 Hz alpha ERD was lower (in lateral and medial pre-motor areas) during right handed wrist movements in competitive athletes than in non-athletes. In addition, Bablioni et al. (2010) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were 16 elite karate athletes, 15 amateur karate athletes, and 17 non-athletes who judged videos of karate movements. Bablioni et al. recorded spontaneous EEG activity, specifically low alpha and high alpha ERD and performed source localization using the LORETA algorithm. They reported that elite athletes were more accurate in judging karate videos than novice athletes. They also experienced less low and high frequency alpha ERD (in Broadmann's dorsal area) compared to novice athletes. Additionally, Del Percio, Infarinato et al. (2011) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were 18 elite karate athletes and 28 non-athletes who completed periods of resting with eyes open and eyes closed. Del Percio, Infarinato et al. recorded event-related EEG activity, specifically low alpha and high alpha ERD. They performed source localization using the Laplacian transformation algorithm. The results showed that competitive athletes had less low and high frequency alpha ERD (at frontal, parietal, and occipital sites) when moving from eyes open to eyes closed than did the non-athletes. As mentioned previously, Ermutlu et al. (2015) used a between-subject design to examine EEG activity different athletes. In addition to the findings described earlier in this section, they also reported that dancers had a higher level of alpha activity than did ball players or non-athletes.

A few studies recorded beta and/or gamma activity in competitive athletes and non-athletes. Each of these studies have been mentioned previously. For example, Wang et al. (2015) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. In addition to the findings described earlier in this section, they also reported that athletes (i.e., badminton players) had faster reaction times and were more accurate than non-athletes. This performance difference was accompanied by decreased beta activity in competitive athletes relative to non-athletes. Likewise, Ermutlu et al. (2015) used a between-subject design to examine EEG activity different athletes. In addition to the findings described earlier in this section, they also reported that dancers had a higher level of beta activity than did ball players or non-athletes.

A single study recorded SMR activity in in competitive athletes and non-athletes. As mentioned previously, Ziółkowski et al. (2014) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. In addition to the findings described earlier in this section, they also reported that there was more SMR activity in competitive athletes than in non-athletes.

A few studies recorded EEG coherence in competitive athletes and non-athletes. For example, Del Percio, Iacoboni et al. (2011) used a between-subject design to compare sport-related EEG activity in experts and novices. Participants were 18 elite shooters and 10 non-athletes who performed 120 pistol shots. Del Percio et al. recorded spontaneous EEG activity, specifically theta, low alpha, high alpha, low beta, high beta, and gamma coherence. Moreover, they performed source localization using the Laplacian transformation algorithm. They reported that both intra-hemispheric and inter-hemispheric low alpha, high alpha, high beta, and gamma coherence were stable across the pre-performance period in elite shooters. Both intra-hemispheric and inter-hemispheric coherences were unstable across the pre-performance period in non-athletes. Similarly, Velikova et al. (2012) used a mixed model design to compare sport-related EEG activity between competitive athletes and non-athletes during eyes-open and eyes-closed conditions. Participants were 13 expert fencers and 13 non-athletes who completed several conditions, including maintaining eyes open, maintaining eyes closed, making in-phase movements, and making anti-phase movements. Velikova et al. recorded spontaneous EEG activity, specifically delta, theta, alpha2, alpha2, beta1, beta2, beta3, and gamma coherence. They performed source localization using the LORETA algorithm. The results showed that fencers had higher alpha2 coherence (between the posterior cingulate cortex and the right angular gyrus) and higher delta coherence (between the left middle frontal gyrus and the left temporal gyrus) than non-athletes.

More than a few, studies recorded event-related potentials in competitive athletes and non-athletes. Among them, Rossi, Zani, Taddei, and Pesce (1992) used a mixed-model design to compare sport-related EEG activity between athletes and non-athletes. Participants were 11 expert fencers and 10 non-athletes who performed an auditory discrimination (Go/No-Go) reaction time task. Rossi et al. recorded event-related EEG activity, specifically including the N2 and P300 waveforms. The results indicated that the fencers evidenced faster reaction times and shorter latencies for the N2 and P300 waveforms than the non-athletes. Following along these lines, Di Russo, Taddei, Apnile, and Spinelli (2006) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were 12 expert fencers and 12 non-athletes who completed 400 trials of a discriminative (Go/No-go) reaction time task. Di Russo et al. recorded event-related EEG activity, specifically including the P1, N1, P2, N2, and P300 waveforms. They performed source localization using the Brain Electrical Source Analysis algorithm. They found that the competitive athletes had faster reaction times (for the discrimination task) than the non-athletes. In addition, there were significant event-related potential differences between competitive athletes and non-athletes. The amplitude for the N1 waveform was larger in competitive athletes than in non-athletes. Similarly, the amplitude for the No-go (the inhibition) N2 and P3 amplitudes were larger in competitive athletes than in non-athletes. Likewise, Taddei, Bultrini, Spinelli, Di Russo, and Francesco (2012) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were 10 older fencers, 10 younger fencers, 10 older non-athletes, and 10 younger non-athletes who performed a simple reaction time task and a discrimination (Go/No-Go) reaction time task. Taddei et al. recorded event-related EEG activity, specifically including the P1, N1, P2, N2, and P300 waveforms. They performed source localization using the Brain Electrical Source Analysis algorithm. The results revealed that competitive athletes had faster reaction times and more false alarms than non-athletes. These differences were accompanied by between-subject differences in event-related potentials. Specifically, the competitive athletes had shorter latencies and larger amplitudes for the P1 and the N2 waveforms than the non-athletes. In addition, the competitive athletes had larger amplitude P3 waveforms (in the inhibition/No-Go condition) than non-athletes.

Several studies recorded slow potentials in competitive athletes and non-athletes. Among them, Kita, Mori, and Nara (2001) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were four kendo players, two gymnasts, and nine non-athletes who performed brief, self-paced wrist extensions of the right hand. Kita et al. recorded event-related EEG activity, specifically movement-related cortical potentials. They focused on the Bereitschaftspotential, the negative slope, and the motor potential. In addition, they recorded EMG activity (from the right wrist extensor muscles). They reported that the integrated amplitude of the EMG was larger in the competitive athletes than in the non-athletes. In addition, the Bereitschaftspotentials were smaller, in the competitive athletes than in the non-athletes. More recently, Del Percio et al. (2008) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were 11 elite fencing athletes, 11 elite karate athletes, and 11 non-athletes who observed 200 pictures (of either fencing or karate attacks) and decided whether the attacks looked like right or left side attacks. Del Percio et al. recorded event-related EEG activity, specifically movement-related cortical potentials. They focused on the readiness and the motor potential waveforms and performed source localization using the Laplacian transformation algorithm. The results indicated significant between-subject differences in movement-related cortical amplitudes during the karate/fencing attack judging task. The amplitudes of the readiness potential and the motor potential (at C3 and Cz) were smaller in competitive athletes than in non-athletes. In addition, Nakamoto and Mori (2008) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were nine college baseball players and nine non-athletes who performed an anticipation timing (Go/No-go) reaction time task with varying levels of stimulus response compatibility (i.e., compatible with baseball batting and not compatible with baseball batting). Nakamoto et al. recorded event-related EEG activity, specifically movement-related cortical potentials. They focused on the CNV. They reported that competitive athletes had faster reaction times than non-athletes (in Go trials) and shorter lateralized readiness potential onsets. Likewise, Hatta, Nishihira, Higashiura, Kim, and Kaneda (2009) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were eight elite kendo players and eight non-athletes who performed 70 trials each of a left and right hand grip task (i.e., squeezing a dynamometer). Hatta et al. recorded event-related EEG activity, specifically movement-related cortical potentials. They focused on the Bereitschaftspotential, the negative slope, and the motor potential. Additionally, they recorded EMG activity from forearm extensor muscles. The results showed that the onset of the Bereitschaftspotential (for the non-dominant handgrip) was shorter in the competitive athletes than in the non-athletes. In addition, the peak amplitude of the motor potential was larger in the kendo players than in the non-athletes.

Last, more than a few studies recorded evoked potentials in competitive athletes and non-athletes. Among them, Thomas and Mitchell (1996) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were 10 endurance runners, seven elite gymnasts, and seven non-athletes who completed a period of somatosensory stimulation (using a Nihon Kohden Electromyograph with stimulating electrodes attached to the wrist). Thomas et al. recorded event-related EEG activity, specifically somatosensory evoked potentials (i.e., the P9, P11, P13/14, N20, P25, and N30 waveforms). They also measured reaction times. They found no significant between-subject differences in any of the components of the somatosensory waveform or in the reaction times. Continuing this line of inquiry, Thomas, Harden, and Rogers (2005) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were 25 elite cricketers and 10 non-athletes who completed a period of visual stimulation (i.e., watching an alternating checkerboard pattern). Thomas et al. recorded event-related EEG activity, specifically visual evoked potentials (i.e., the N70, P100, and N145 waveforms). In addition, they measured choice reaction times. They found no differences in choice reaction time task performance between competitive athletes and non-athletes. However, the latencies for the visual evoked potential waveform (i.e., the N70) were shorter for the competitive athletes than for the non-athletes. Delpont, Dolisi, Suisse, Bodino, and Gastaud (1991) used a between-subject design to examine EEG activity in competitive athletes and non-athletes. Participants were 24 skilled tennis players, 24 skilled rowers, and 24 non-athletes who completed a period of visual stimulation (i.e., watching an alternating checkerboard pattern). Delpont et al. recorded event-related EEG activity, specifically visual evoked potentials. They reported that the tennis players had shorter visual evoked potential latencies (i.e., for the two P100s) than did the rowers or the control subjects. Similarly, Taddei, Viggiano, and Mecacci (1991) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were eight expert fencers and eight non-athletes who completed a period of visual stimulation (i.e., watching an alternating checkerboard pattern) in two conditions – a large visual field and small visual field. Taddei et al. recorded event-related EEG activity, specifically visual evoked potentials (i.e., the P60-N75, N75-P100, and P100-N145 waveforms). The results showed that the latencies for the N75 waveform were shorter in the right hemisphere in the competitive than in the non-athletes. In addition, the amplitudes for the N75-P100 waveforms were larger in the left hemisphere in the competitive athletes than in the non-athletes. The latencies for the P100 waveform were shorter in the competitive athletes (in both hemispheres) than in the non-athletes. In addition, Martin, Delpont, Suisse, and Dolisi (1993) used a between-subject design to compare sport-related EEG activity in competitive athletes and non-athletes. Participants were 24 tennis players, 24 rowers, and 24 non-athletes who completed a period of monaural stimulation (i.e., listening to ‘clicks’ presented to right and left ears). Martin et al. recorded event-related EEG activity, specifically brainstem auditory evoked potentials. They reported that the latencies for five (out of 13) of the brainstem auditory evoked potentials examined were shorter in the competitive athletes (i.e., the tennis players) than in the non-athletes. In addition, the amplitudes for one (out of nine) brainstem auditory evoked potentials were larger in the competitive athletes (i.e., the tennis players) than in the non-athletes.

In summary, there were 27 studies that examined differences in sport-related EEG activity between competitive athletes and non-athletes. The majority of these examined differences in theta activity (n=4), alpha activity (n=6), slow potentials (n=4), or evoked potentials (n=5) between competitive athletes and non-athletes. A few studies examined differences in beta activity (n=2), SMR activity (n=1), EEG coherence (n=2), and event-related potentials (n=3). Across these studies, three points of agreement emerged. First, there seems to be a consensus that theta and alpha activity are higher in competitive athletes than in non-athletes. Three out of the four studies reviewed reported that theta activity was higher in competitive athletes than in non-athletes. The exception reported (Ziółkowski et al., 2014) that theta activity was lower in competitive athletes than in non-athletes. Moreover, all of the studies reviewed reported that alpha activity was higher in competitive athletes than in non-athletes. Second, there seems to be a consensus that event-related potential latencies are shorter and/or their amplitudes are larger in competitive athletes than in non-athletes. All of the studies reviewed reported that event-related potential latencies were shorter and/or their amplitudes were larger in competitive athletes than in non-athletes. Third, there seems to be a consensus that evoked potential latencies are shorter in competitive athletes than in non-athletes. All five of the studies reviewed reported that evoked potential latencies were shorter in competitive athletes than in non-athletes.

How Is EEG Activity Different in Disabled and Non-disabled Athletes?

A few studies recorded EEG activity in disabled and non-disabled athletes. For example, Kim and Woo (2013) used a between-subject design to examine EEG activity disabled and non-disabled shooters. Participants were 12 disabled air pistol shooters and 22 non-disabled elite shooters who performed 20 self-paced shots using the SCATT Shooter Training system. Kim and Woo recorded spontaneous EEG activity, specifically alpha activity and alpha asymmetry (R-L). They reported that there were no differences in shooting performance between disabled and non-disabled shooters. Nonetheless, there were EEG-related differences between the two groups of shooters. Disabled shooters had more left hemisphere activation (i.e., less left hemisphere alpha activity) than non-disabled shooters. Shooting scores were correlated (r’s @.6) with alpha asymmetry scores. In addition, Kim, Lee, Kim, and Woo (2013) used a between-subject design to examine EEG activity disabled and non-disabled shooters. Participants were 12 disabled air pistol shooters and 22 non-disabled elite shooters who performed 20 self-paced shots using the SCATT Shooter Training system. Kim et al. recorded spontaneous EEG activity, specifically theta, low alpha, high alpha, beta, and gamma coherence. They found no differences in shooting performance between disabled and non-disabled shooters. Still, there were EEG-related differences between the two groups of shooters. Disabled shooters had higher theta (at Fz/T4), low alpha (at Fz/C4, Fz/T4, and Fz/T3), beta, and gamma (at frontal and central sites) coherence during the pre-performance period than non-disabled shooters.

In summary, there were two studies that examined differences in sport-related EEG activity between disabled and non-disabled athletes. Both studies reported differences in sport-related EEG activity between disabled and non-disabled athletes. Specifically, Kim and Woo (2013) found less left hemisphere alpha activity in disabled than in non-disabled athletes and Kim et al. (2013) found higher coherence (i.e., theta, alpha, beta, and gamma coherence) in disabled than in non-disabled athletes. Given the paucity of research, it's impossible to answer the question about disabled and non-disabled athletes at this point in time.

How Does Practice/Learning Change EEG Activity?

Several studies examined the effects of practice/learning on EEG activity. Among those, Landers et al. (1994) used a within-subject design to examine EEG activity pre- and post-training. Participants were 11 novice archers who performed an archery shooting task (shooting arrows at a target) before and after a 15-w archery training class. Landers et al. recorded spontaneous EEG activity, specifically 4–30 Hz activity. They focused on EEG asymmetry and also measured heart rate. The results revealed that performance improved and heart rate deceleration increased from pre- to post-test. In addition, alpha power at T3 increased after archery training and alpha power at T4 did not. Furthermore, there were no significant hemispheric differences (no asymmetry) at the pretest. However, there were significant hemispheric differences (negative asymmetry) at the post-test. Similarly, Kerick, Douglass, and Hatfield (2004) used a multi-factorial design to compare EEG activity pre- and post-training and across two different tasks. Participants were 11 novice pistol shooters who performed a shooting and a postural simulation task at two different time periods (i.e., before and after a 12–14 week training period). Kerick et al. recorded spontaneous EEG activity, specifically high alpha activity. They reported that performance increased across time during the training period. This was accompanied by an increase in event-related high alpha power during shooting (at T3 but not T4) across time during the training period. Likewise, Domingues et al. (2008) used a within-subject design to examine EEG activity performance across learning trials. Participants were 23 novice pistol shooters who performed four blocks of 10 shots each. Domingues et al. recorded spontaneous EEG activity, specifically alpha activity. They found that accuracy increased across learning trials. This performance effect was accompanied by decreased alpha power (at F3 and F4 and F7 and F8) across learning trials.

In summary, there were only three studies that examined the effects of learning on sport-related EEG activity. All three reported changes in alpha activity from pre- to post-tests. Landers et al. (1994) reported increased left hemisphere alpha activity from before to after 15 weeks of archery training. Kerick et al. (2004) reported increased left hemisphere alpha activity from before to after 12–14 weeks of shooting training. Domingues et al. (2008), however, reported increased left and right hemisphere (i.e., at F3, F4, F7, and F8) activity across a series of practice sessions (i.e., 4 blocks of 10 shots each). Given the paucity of research, it's impossible to definitively answer the question about learning and EEG activity at this point in time. However, the research to date suggests that learning results in increased sport-related alpha activity (specifically left hemisphere alpha activity).

Is EEG Activity during a Sport Task Different from EEG Activity during Other Tasks (e.g., Balancing on a Stabilometer)?

Several early (pre-2000) studies compared the effects of different tasks on EEG activity. For example, Hatfield et al. (1984, Study 2) used a within-subject design to compare sport-related EEG activity during different tasks. Participants were 15 collegiate shooters who performed an air rifle shooting and two non-shooting tasks (i.e., a verbal-analytic task and a visuospatial task). Hatfield et al. recorded spontaneous EEG activity, specifically alpha activity and alpha asymmetry. The results revealed that EEG activity during shooting was not significantly different from EEG during the visuospatial task. Using a similar approach, Salazar et al. (1990) used a multi-factorial design to compare sport-related EEG activity during different tasks. Participants were 13 male and 15 female archers who performed four tasks, including shooting with normal bow, shooting with light bow, bow drawing without aiming, and aiming without bow drawing. Salazar et al. recorded spontaneous EEG activity, specifically 5–31 Hz activity. They reported that there were significant differences in EEG activity across conditions. For the relaxation condition, there were significant within-subject differences for 6–12 Hz EEG activity. For the full-draw (2 kg bow) condition, there were significant within-subject differences for 10–16 Hz EEG activity. For the next full-draw (18 kg bow) condition, there were significant within-subject differences for 10–14 Hz EEG activity. Finally, for the shooting condition, there were significant within-subject differences for 12–14 Hz EEG activity. Using a different approach, Konttinen and Lyytinen (1993b) used a within-subject design to compare sport-related EEG activity in four different tasks. Participants were eight novice shooters who performed four different shooting tasks varying on motor and visual components. Konttinen et al. recorded event-related EEG activity, specifically slow potentials. They recorded heart rate, respiration, and rifle stability. They found differences in slow potentials across the different tasks. Participants evidenced less slow potential negativity (i.e., more slow potential positivity) during the more motor/less visual targeting-related task and more slow potential negativity during the less motor/more visual targeting-related task. In addition, Haufler et al. (2000) used a mixed-model design to compare sport-related EEG activity across several tasks. Participants were 15 elite shooters and 21 novice shooters who performed simulated rifle shooting and visuospatial and verbal tasks. Haufler et al. recorded spontaneous EEG activity, specifically theta, low alpha, high alpha, beta, and gamma activity. They reported that EEG asymmetry during shooting was lower than in the dot localization task (for experts only). In addition, EEG asymmetry during shooting was like that in the word finding task. This was not true for novices. EEG asymmetry was similar across tasks for novices. Along this line, Kerick et al. (2001) used a within-subject design to compare sport-related EEG activity during different tasks. Participants were eight skilled marksmen who performed shooting, posture control, and movement control tasks. Kerick et al. recorded event-related EEG activity, specifically event-related alpha activity. The results indicated that event-related alpha power was higher before shooting than the posture or movement control tasks.

In summary, five studies compared sport-related EEG activity with EEG activity during other tasks. A couple of these (Hatfield et al., 1984; Haufler et al., 2000) compared EEG activity during shooting with EEG activity during verbal-analytic and visuospatial tasks. Both reported that EEG activity during shooting was most like EEG activity during visuospatial tasks. Moreover, Salazar et al. (1990) found difference in EEG activity between shooting an arrow, aiming an arrow at a target, and holding a drawn bow (without aiming at a target). Likewise, Kerick et al. (2001) found more alpha activity before shooting than before movement control or posture control tasks. Finally, using a different metric, Konttinen and Lyytinen (1993b) found less slow potential negativity during a more motor/less visual targeting type task and more slow potential negativity during a less motor/more visual targeting type task.

Is Sport-Related EEG Activity Changed by Socio-Environmental Manipulations (e.g., Adding Competition)?

A few studies examined the effects of pre-task stimulation on EEG activity. Focusing on pre-task audio-visual stimulation, Del Percio, Marzano et al. (2007) used a multi-factorial design to compare sport-related EEG activity between athletes and non-athletes and across two levels of pre-task audio-visual stimulation. Participants were 14 elite fencing athletes and 14 non-athletes who observed 80 pictures (of either fencing or karate attacks). The picture judging task was performed in two conditions, with and without pre-task (10 Hz) audio-visual stimulation. Del Percio et al. recorded event-related EEG activity, specifically alpha ERD. They also measured reaction times. They reported that pre-task audio-visual stimulation (at a 10 Hz frequency) improved reaction times and increased alpha power. Focusing on pre-task exercise, Luchsinger et al. (2016) used a mixed-model design to compare sport-related EEG activity across resting and post-exercise performances. Participants were nine biathletes and eight non-athletes who performed 100 shots using the SCATT Shooter Training system. The shooting task was performed in two conditions, resting and post-exercise (i.e., five-minute in-line skating). Luchsinger et al. recorded spontaneous EEG activity, specifically frontal theta activity. In addition, they measured perceived exertion (using a Borg scale) and self-reported concentration (using a visual analog scale). They reported no significant effects of exercise on frontal theta activity in either biathletes or non-athletes.

In addition, a few studies examined the effects of attentional manipulations on EEG activity. For example, Radlo, Steinberg, Singer, Barba, and Melnikov (2002) used a between-subject design to compare the effects of different attention-focusing strategies on sport-related EEG activity. Participants were 20 novice dart throwers who performed 10 blocks of four dart throws in one of two conditions. Dart throws were performed either using an internal attention-focusing strategy or using an external attention-focusing strategy. Radlo et al. recorded spontaneous EEG activity, specifically alpha power. They also recorded heart rate and EMG activity. The results showed that dart throwers using the external attention-focusing strategy performed better (i.e., had less absolute error) than those using the internal attention-focusing strategy. They also had lower heart rates and a lower level of alpha activity than those in the internal attention condition. Along the same lines, Zhu, Poolton, Wilson, Maxwell, and Masters (2011) conducted two studies examining the effects of self-monitoring-related manipulations on sport-related EEG activity. Study 1 used a between-subject design to compare sport-related EEG activity high self-monitoring and low self-monitoring athletes. Participants were 16 novice golfers (varying on tendency to self-monitor) who performed a putting task. Zhu et al. recorded spontaneous EEG activity, specifically alpha1 and alpha2 coherence. In addition, they measured the athletes' tendencies to self-monitor (using the Movement Specific Reinvestment Scale). They reported that participants who tended to self-monitor had more T3-Fz alpha coherence than those who did not tend to self-monitor. Extending the results of Study 1, Zhu et al. (2011)'s second study used a between-subject design to compare sport-related EEG activity during implicit and explicit practice. Implicit practice has been shown to be associated with "reduced verbal-analytical involvement in movement control" (Zhu et al., 2011, p. 67) in comparison with explicit practice. Participants were 18 novice golfers randomly assigned to implicit and explicit practice conditions who performed a putting task. Zhu et al. recorded spontaneous EEG activity, specifically alpha1 and alpha2 coherence. The results indicated that participants who experienced explicit practice on golf putting task had a higher level of alpha (T3-Fz) coherence than those who experienced implicit practice. In addition, Reinecke et al. (2011) indirectly manipulated attentional focus. That is, they used a within-subject design to compare sport-related EEG activity during different tasks. Participants were 11 collegiate golfers who performed self-paced putts in two conditions, inside and outside. Reinecke et al. recorded spontaneous EEG activity, specifically theta, alpha1, alpha2, and beta1 activity. They also measured state anxiety (using the State-Trait Anxiety Inventory). The results showed no significant differences in state anxiety between the two conditions. Nonetheless, participants had higher F4 theta activity during putting than during rest and higher F4 theta activity when putting in the field than when putting in the lab.

A single study examined the effects of winning on EEG activity. Hunt, Rietschel, Hatfield, and Iso-Ahola (2013) used a between-subject design to examine EEG activity winning athletes and losing athletes. Participants were 17 collegiate/ROTC volunteers who completed 40 shots using the NOPTEL Shooter Training system in a head-to-head competition with another participant. Participants were assigned to either the 'winning' group (n=10) or 'losing' group (n=7) depending on whether they won or lost the competition. Hunt et al. recorded spontaneous EEG activity, specifically delta, theta, alpha, low alpha, high alpha, beta, and gamma activity. They also measured confidence levels. They found that winners had the same level of performance, and a higher level of confidence, as losers. This was accompanied by less high alpha power and less theta power (in both hemispheres) in winners than in losers. The differences in alpha and theta power were clear during all pre-shot epochs.

Several studies examined the effects of applying pressure (i.e., making tasks competitive) on EEG activity. For example, Cooke et al. (2014) used a mixed-model design to compare sport-related EEG activity across high and low pressure conditions. Participants were 10 expert golfers and 10 novice golfers who performed 60 putts. The putting task was performed under two conditions, low-pressure (non-competitive) and high-pressure (competitive). Cooke et al. recorded spontaneous EEG activity, specifically theta, low alpha, high alpha, and beta activity. They also recorded number of putts holed, self-reported pressure, movement kinematics, heart rate, and EMG activity. They reported few effects of the high/low pressure manipulation. Although there were differences in self-reported pressure and heart rate, there were no within-subject differences in number of putts holed. There were also no differences in movement kinematics, in EMG activity, or in spontaneous EEG activity between the high and low pressure conditions. Similarly, Gallicchio et al. (2015) used a mixed-model design to compare sport-related EEG activity across high and low pressure conditions. Participants were 10 expert golfers and 10 novice golfers who performed 60 putts. The putting task was performed in two conditions, low-pressure (non-competitive) and high-pressure (competitive). Gallicchio et al. recorded spontaneous EEG activity, specifically left and right hemisphere alpha coherence. They also recorded number of putts holed. They found no effects of the high/low pressure manipulation. There were no within-subject differences in number of putts holed or in left or right hemisphere alpha coherence. In addition, Hatfield et al. (2013) used a within-subject design to compare sport-related EEG activity during high and low pressure conditions. Participants were 19 ROTC student volunteers who performed 40 shots using the Noptel Shooter Training system in competitive (included time constraints and rewards/penalties) and non-competitive conditions. Hatfield et al. recorded event-related EEG activity, specifically alpha ERD/ERD. They also recorded movement kinematics, state anxiety, and cortisol levels. The results revealed that self-reported anxiety, salivary cortisol, and alpha coherence (between Fz and all other recording sites) were higher when shooting competitively than when shooting alone. In addition, shooting competitively was also associated with lower 10–13 Hz alpha activity.

Several studies examined the effects of manipulating task type, task difficulty, or type of feedback on EEG activity. Focusing on the effects of task difficulty, Collins, Powell, and Davies (1990) used a within-subject design to compare sport-related EEG activity during different tasks. Participants were eight male karate experts who performed easy and difficult board breaking tasks. Collins et al. recorded spontaneous EEG activity, specifically alpha activity. The results showed no significant between-task differences in EEG activity. Comparing different sport athletes, Rossi and Zani (1991) used a within-subject design to compare sport-related EEG activity during different tasks. Participants were four skilled skeet-shooters and four skilled trap-shooters who performed an auditory discrimination task with two levels of difficulty, easy and difficult. Rossi et al. recorded event-related EEG activity, specifically including the N2 and P300 waveforms.

They reported that the skeet-shooters had earlier latencies for the N2 and P300 waveforms than the trap-shooters. In addition, Vrbik, Bene, and Vrbik (2015) used a within-subject design to examine sport-related EEG activity in athletes doing different types of archery. Participants were four experienced, recurve bow archers and four experienced, compound bow archers who shot 12 arrows. Vrbik et al. recorded spontaneous EEG activity, specifically attention' and 'meditation' scores (i.e., as derived from Mindwave Mobile Software algorithms). They reported EEG-related differences between compound bow shooters and recurve bow shooters. Compound bow shooters had higher EEG attention and lower EEG meditation scores pre, during, and post shooting compared to recurve bow shooters. Similarly, Rossi et al. (1992) used a mixed-model design to compare sport-related EEG activity across easy and difficult tasks. Participants were 11 expert fencers and 10 non-athletes who performed an auditory discrimination (Go/No-Go) reaction time task with two levels, easy and difficult. Rossi et al. recorded event-related EEG activity, specifically including the N2 and P300 waveforms. They also measured reaction times. They reported that both reaction times and N2 and P300 latencies were longer for the difficult task. Along the same lines, Kerick, Hatfield, and Allender (2007) used a within-subject design to compare sport-related EEG activity during different tasks. Participants were 14 experienced shooters who performed a simulated shooting task, involving decision (enemy/no-enemy) and no-decision conditions. Requiring the enemy/no-enemy decision before shooting increases task difficulty. Kerick et al. recorded spontaneous EEG activity, specifically theta and upper alpha activity. They reported that theta peak amplitude was higher (at P3 and Pz) and alpha peak amplitude was lower (at C3) in choice relative to no-choice tasks. Focusing on the effect of 'false' feedback, Kerick, Iso-Ahola, and Hatfield (2000) used a within-subject design to examine EEG activity during different types of feedback. Participants were 17 novice rifle shooters who performed 40 shots in a seated position (with the rifle supported by a shooting stand). The shooting task was performed in four different conditions, including no-feedback (about performance), false/low performance feedback, false/moderate performance feedback, and false/high performance feedback. Kerick et al. recorded spontaneous EEG activity, specifically alpha asymmetry. In addition, they measured subjective performance (using the Subjective Performance Questionnaire) and affect (using the Positive and Negative Affect Scale). The results indicated that performance was worse and affect was more negative in the false/low performance feedback condition than in the no-feedback and false/moderate performance feedback conditions. This was not accompanied by significant differences across feedback conditions in alpha (F3/F4) asymmetry.

Several studies examined the effects of performing with an audience on EEG activity. For example, Shelley-Tremblay, Shugrue, and Kline (2006) used a within-subject design to compare sport-related EEG activity during high and low pressure conditions. Participants were 20 novice golfers who performed 20 putts. The putting task was performed in a low pressure (no audience) condition and in a high pressure (audience watching) condition. Shelley-Tremblay et al. recorded spontaneous EEG activity, specifically alpha, beta1, and beta2 activity. They also measured mood states (using the Profile of Mood States questionnaire). They found that putting accuracy decreased in the audience condition relative to the no-audience condition. This performance decrement was accompanied by an increase in beta activity in the audience condition. Interestingly, beta activity was positively related (r's @.6) to error/distance from hole. The higher the level of beta activity (i.e., at C3, C4, and T4), the farther the distance from the hole. Similarly, Rietschel et al. (2011) used a within-subject design to compare EEG activity in high and low pressure (i.e., presence/absence of social evaluation). Participants were 13 college student volunteers who completed 60 trials of a visuo-motor pointing task in two conditions. The task was performed alone and with social evaluation (i.e., two confederates standing just behind the participant). Rietschel et al. recorded spontaneous EEG activity, specifically low alpha, high alpha, and gamma coherence. In addition, they recorded heart rate and skin conductance. The results indicated that arousal was higher and performance was better in the social evaluation condition. Specifically, heart rate was higher, skin conductance levels were higher, self-reported stress was higher, and the variability of the aiming trajectory was lower in the social evaluation condition. This was accompanied by increased beta coherence (in the frontal, left central, parietal, and occipital areas) and increased gamma coherence (in the temporal areas) in the social evaluation condition. It was also accompanied by decreased beta coherence (in the right temporal areas) in social evaluation condition.

In summary, 19 studies examined the effects of four broad types of socio-environmental manipulations on sport-related EEG activity. First, there were two studies that examined the effects of pre-task stimulation on sport-related EEG activity. Only pre-task audio-visual stimulation (Del Percio, Marzano et al., 2007) had an impact on reaction time and alpha activity in athletes judging fencing attacks. Second, there were five studies that examined the effects of either task type or task difficulty on sport-related EEG activity. Among these, Collins et al. (1990) found no differences in alpha activity for harder compared to easier tasks. In contrast, Rossi et al. (1992) found increased event-related potential latencies (i.e., N2 and P300 latencies) for harder compared to easier tasks. Likewise, Kerick et al. found more theta activity and less alpha activity in difficult compared to easy tasks. Moreover, Rossi and Zani (1991) found earlier event-related potential latencies (i.e., N2 and P300 latencies) for skeet-shooters compared to trap-shooters; and Vrbik et al. (2015) found EEG differences between compound bow shooters and recurve bow shooters. Third, there were four studies that examined the effects of attentional manipulations on sport-related EEG activity. One study found that focusing externally decreased alpha activity and improved performance. Another study found that putting outdoors increased theta activity compared to putting indoors. Two other studies found that participants that tended to do more self-monitoring and participants that used explicit practice strategies had higher levels of EEG coherence. Fourth, there were several studies (n=8) that examined the effects of either competition or of some other way of 'pressuring' athletes. Of these, four studies manipulated pressure/competition and found effects on performance and EEG activity. Among these, Hunt et al. (2013) found that winning a competition was associated with less theta and alpha activity than losing the competition. Similarly, Hatfield et al. (2013) found that shooting competitively resulted in increased state anxiety, increased salivary cortisol, decreased alpha activity, and increased alpha coherence in comparison with shooting non-competitively. Additionally, Shelley-Tremblay et al. (2006) found that performing in front of an audience negatively impacted performance (and mood states) and also increased beta activity. Further, Rietschel et al. (2011) also examined the effects of performing in front of an audience. They found that performing in front of an audience improved performance (and self-reported stress) and increased beta and gamma coherence (i.e., in most, but not all of the areas measured). However, there were also three studies that reported nonsignificant effects of pressure/competition manipulations. That is, Cooke et al. (2014) and Gallicchio et al. (2015) manipulated pressure/competition as golfers attempted to sink putts. Neither of these studies reported significant effects of the pressure/competition manipulations. Likewise, Kerick et al. (2000) found that false feedback (i.e., informing participants that they performed worse than they did) impaired shooting performance (and negatively impacted affect), but did not impact EEG asymmetry. Across these studies, the consensus seems to be that manipulations that increase the athlete's stress levels and/or change the athlete's attentional focusing strategy impact sport-related EEG activity.

Conclusion

This chapter reviewed the literature examining sport-related EEG activity over the past quarter-century and focused on eight questions, including questions related to changes in EEG activity across the pre-performance period, differences in EEG activity between good and poor performances, differences in EEG activity between experts and novices, differences in EEG activity between competitive athletes and non-athletes, differences in EEG activity between disabled and non-disabled athletes, effects of practice on sport-related EEG activity, effects of different tasks on sport-related EEG activity, and effects of socio-environmental manipulations on sport-related EEG activity. Ninety-two research studies were reviewed and five main conclusions were drawn.

1 There seems to be a consensus that alpha activity (particularly in the left hemisphere) increases across the pre-performance period. With regard to increasing left hemisphere alpha activity, Janelle and Hatfield (2008) noted that the "hypothesis was that superior performance would be characterized by attenuation of activity in the left temporal region in light of the automaticity of expert performance and the need to reduce possible interference from analysis and overthinking" (p. S50).

2 There seems to be a consensus that beta activity is lower, and that slow potential shifts are less negative, in good performances than in poor performances. With regard to lower beta activity in good versus poor performances, it is worth noting that beta activity has been interpreted as indicative of cognitive effort and/or as increased anxiety (Crews & Landers, 1993). Moreover, Shelley-Tremblay et al. (2006) noted that the "positive correlations [between beta activity and distance from the hole] in all cases indicate that greater beta activity was correlated with … less accuracy" (p. 364).

3 There seems to be a consensus that theta activity and alpha activity are higher, and that EEG coherence is lower, in experts than in novices. With regard to higher theta and alpha activity in experts versus novices, Kerick et al. (2007) noted that

> theta and alpha provide unique but complementary information that together yield an enhanced ability to monitor cognitive load. More specifically, the theta peak appears related to working memory for stimulus encoding and decision making, whereas the progressive increase in alpha appears related to focused motor preparation.
>
> *(p. B163)*

With regard to lower EEG coherence in experts versus novices, Cooke (2013) noted that

> the increased accuracy of experts compared to novices in both shooting and golf… could be reflected by … a reduction in EEG alpha power coherence between the left temporal and frontal midline regions of the brain during preparation for action in both shooting and golf.
>
> *(p. 132)*

4 There seems to be a consensus that theta and alpha activity are higher, that event-related potential latencies are shorter and/or their amplitudes are larger, and that evoked potential latencies are shorter in competitive athletes than in non-athletes. With regard to shorter event-related potential latencies and larger amplitudes, it is worth noting that event-related potentials have been interpreted as a "reflection of neural synchronization" (Del Percio, Brancucci et al., 2007, p. 110). Moreover, Del Percio, Brancucci et al. (2007) noted that "peculiar mechanisms of occipital neural synchronization can be observed in elite athletes during visuo-spatial demands, possibly to underlie sustained visuo-spatial attention and self-control" (p. 104).

5 There seems to be a consensus that manipulations that increase the salience of competition/winning, increase the athlete's stress levels and/or change the athlete's attentional focusing strategy impact sport-related EEG activity. Among the studies reporting significant effects (Hatfield et al., 2013; Hunt et al., 2013; Shelley-Tremblay et al., 2006), the direction of the effects seemed to be towards increased activation (i.e., less theta activity, less alpha activity, and more beta activity).

In conclusion, a recurent theme in the studies reviewed was the notion of 'efficiency/economy'. Early on, Hatfield et al. (1987) mentioned "information processing efficiency" (p. 542) as part of the rationale for their study. Following their lead, Hatfield and Kerick (2007) said that the "relevance of this work to the sport practitioner lies in the overwhelming support in the scientific literature for the notion that high-level performance is marked by economy of brain activity that underlies mental processes" (p. 106). Similarly, Baumeister et al. (2008) noted that the "fndings suggest that with increasing skill level, golfers have developed task solving strategies … and an economy in neural activity" (p. 630). Likewise, Janelle and Hatfield (2008) reported that the "corpus of research that has been conducted to date … clearly supports the notion of efficiency or economy of cortical processes" (p. S 49). Additionally, Mann et al. (2011) said that the "significant relationship between right-central (i.e., C4) cortical activation and QE duration … speaks to the cognitive advantage of the expert and supports the notion of relative sensorimotor efficiency of expert athletes" (p. 231). In line with the previous literature, the main conclusions of this chapter (i.e., increased alpha across the pre-performance period in elite athletes, lower beta and less negative slow potential shifts in good performances, higher alpha and theta activity in experts/competitive athletes, and lower EEG coherence in experts) are consistent with the hypothesized relationship between efficient/economical sport-related EEG activity and optimal performance in sport.

Appendix A

Table A1. Methodological details for sport-related EEG studies

Study	*Focus*	*Participants*	*Design*	*Task*	*EEG Variables*	*Other Variables*
Bablioni et al. (2008)	good and poor performance	12 expert golfers	within-subject	performed 10 blocks of 10 putts each (while standing on a balance platform) using a putting green simulator	alpha and beta band activity	body sway
Bablioni et al. (2010)	athletes and non-athletes	16 elite karate athletes, 15 amateur karate athletes, and 17 non-athletes	between-subject	judged videos of karate movements varying with regard to technical and athletic level displayed	low alpha and high alpha band activity (+/-2 Hz individual peak frequency)	
Bablioni et al. (2011)	good and poor performance	12 expert golfers	within-subject	performed 100 self-paced putts using a golf green simulator	low alpha and high alpha band coherence	
Baumeister et al. (2008)	experts and novices	nine experienced golfers and nine novice golfers	between-subject	performed five blocks of 10 putts each using an indoor carpet type putting green	theta, alpha1, alpha2, beta1, and beta2 band activity and EEG asymmetry	anxiety (using the STAI) and stress (using a visual analogue scale)
Bertollo et al. (2016)	good and poor performance	10 elite shooters	within-subject	performed 120 shots	theta, low alpha, and high alpha band ERD/ ERS	
Bird (1987)	good and poor performance	one elite marksman	within-subject	performed a shooting task	peak frequency	
Cheng et al. (2015)	experts and novices	14 expert dart throwers and 11 novice dart throwers	between-subject	performed 60 self-paced dart throws	SMR band ERD/ERS	EMG from forearm flexor muscles
Chuang et al. (2013)	good and poor performance	15 skilled basketball players	within-subject	performed basketball free throw shots	low theta and high theta band activity	
Collins et al. (1990)	different tasks	eight male karate experts	within-subject	performed easy and difficult board breaking tasks	alpha band activity	

Collins, Powell, and Davies (1991)	different tasks	22 physically active volunteers	within-subject	performed repetitions of three motor tasks, including jumping onto a box, doing leg extensions on a leg extension machine, and kicking a soccer ball between two cones	alpha band activity	
Cooke et al. (2014)	experts and novices as a between-subjects factor and high and low pressure as a within-subjects factor	10 expert golfers and 10 novice golfers	mixed-model	performed 60 putts under two conditions, low-pressure (non-competitive) and high-pressure (competitive)	theta, low alpha, high alpha, and beta band activity	movement kinematics, ECG, and EMG
Crews and Landers (1993)	before and during putting	34 highly skilled golfers	within-subject	performed a putting task	theta, alpha, beta1, beta2, and 40 Hz band activity and slow potentials	
Deeny et al. (2009)	experts and novices	15 expert shooters and 21 novice shooters	between-subject	performed 40 self-paced shots using the Noptel Shooter Training System	theta, low alpha, high alpha, low beta, high beta, and gamma band coherence	aiming point
Deeny et al. (2003)	experts and novices	10 expert shooters and nine less skilled shooters	between-subject	Shooting	low alpha, high alpha, and beta band coherence	
Del Percio et al. (2008)	athletes and non-athletes	11 elite fencing athletes, 11 elite karate athletes, and 11 non-athletes	between-subject	observed 200 pictures (of either fencing or karate attacks) and made decisions about whether the attacks were right/left side attacks	single trial epochs	
Del Percio et al. (2010)	athletes and non-athletes	10 elite karate athletes and 12 non-athletes	between-subject	performed wrist extensions of the right and left hands	low alpha and high alpha band activity (+/-2 Hz individual peak frequency)	EMG from operant hand

(*Continued*)

Study	*Focus*	*Participants*	*Design*	*Task*	*EEG Variables*	*Other Variables*
Del Percio, Bablioni, Bertollo et al. (2009)	athletes and non-athletes as a between-subject factor and good and poor performance as a within-subject factor	18 expert shooters and 10 non-athletes	mixed-model	performed 120 shots	low alpha and high alpha band ERD/ERS	
Del Percio, Bablioni, Marzano et al. (2009)	athletes and non-athletes	10 elite karate athletes, 10 elite fencing athletes and 12 non-athletes	between-subject	performed an eyes-open balancing task (i.e., balancing on two feet and balancing on one foot) using a stabilometer	alpha band ERD/ERS	sway index
Del Percio, Brancucci et al. (2007)	experts and novices as one between-subject factor and athletes and non-athletes as another between-subject factor	17 elite karate athletes, 14 amateur karate athletes, and 15 non-athletes	multi-factorial	observed 180 pictures different types of karate attacks and made decisions about whether the attacks were right/left side attacks	visual evoked potentials	
Del Percio, Iacoboni et al. (2011)	experts and novices	18 elite shooters and 10 non-athletes	between-subject	performed 120 pistol shots	theta, low alpha, high alpha, low beta, high beta, and gamma band coherence	
Del Percio, Infarinato et al. (2011)	athletes and nonathletes	18 elite karate athletes and 28 non-athletes	between-subject	completed periods of resting with eyes open and resting with eyes closed	low alpha and high alpha band activity (+/-2 Hz individual peak frequency)	
Del Percio, Marzano et al. (2007)	athletes and non-athletes as a between-subjects factor and with/without pre-task audio-visual stimulation as a within-subjects factor	14 elite fencing athletes and 14 non-athletes	multi-factorial	observed 80 pictures (of either fencing or karate attacks) in two conditions, with and without pre-task (10 Hz) audio-visual stimulation	alpha band ERD/ERS	reaction time

Delpont et al. (1991)	athletes and non-athletes	24 skilled tennis players, 24 skilled rowers and 24 non-athletes	between-subject	completed a period of visual stimulation (i.e., watching an alternating checkerboard pattern)	visual evoked potentials	
di Fronso et al. (2016)	good and poor performance	one elite air pistol shooter	within-subject	performed 40 self-paced shots	theta, low alpha, and high alpha band ERD/ERS	perceived control
Di Russo, Pitzalis, Aprile, and Spinelli (2005)	experts and novices	12 professional clay-target shooters and 12 novice shooters	between-subject	performed three blocks of 50 self-paced finger flexion (i.e., keypad press) movements	movement-related cortical potentials, specifically the Bereitschaftspotential, the negative slope, and the motor potential	
Di Russo et al. (2006)	athletes and non-athletes	12 expert fencers and 12 non-athletes	between-subject	completed 400 trials of a discriminative (Go/No-go) reaction time task	including the P1, N1, P2, N2, and P300 waveforms	
Domingues et al. (2008)	performance across learning trials	23 novice pistol shooters	within-subject	performed four blocks of 10 shots each	alpha band activity	
Doppelmayr et al. (2008)	experts and novices	eight expert shooters and 10 novice shooters	between-subject	performed 10 blocks of five shots each	frontal theta band activity	
Dyke et al. (2014)	good and poor performance	13 novice golfers	within-subject	performed 30 putts. Putts were divided into five most and five least accurate	theta, low alpha, high alpha, low beta, high beta, and gamma band coherence	
Ermutlu et al. (2015)	different types of athletes	12 dancers, 12 fast ball sport athletes and 12 non-athletes	between-subject	completed a five-minute period of ‘awake’ relaxation	delta, theta, alpha, and beta band activity	
Fattapposta et al. (1996)	experts and novices	eight elite pentathletes and eight novice pentathletes	between-subject	completed the Skilled Performance Task (i.e., an interactive bi-manual motor-perceptual task)	movement-related cortical potentials, specifically the Bereitschaftspotential and the skilled performance positivity potential	EMG from forearm flexor muscles

(*Continued*)

Study	Focus	Participants	Design	Task	EEG Variables	Other Variables
Gallicchio et al. (2015)	experts and novices as a between-subjects factor and high and low pressure as a within-subjects factor	10 expert golfers and 10 novice golfers	mixed-model	performed 60 putts under two conditions, low-pressure (non-competitive) and high-pressure (competitive)	alpha band coherence	
Hack et al. (2009)	experts and novices	10 experienced basketball referees and 10 novice basketball referees	between-subject	judged pictures of basketball game situations varying with regard to the presence/absence of a foul	including the N1 and P300 waveforms	
Harung (2011)	different levels of expertise	33 Olympic/ world class and 33 competitive athletes	between-subject	performed two paired reaction time tasks (i.e., tasks that included a warning stimulus followed by an imperative stimulus)	6–40 Hz EEG coherence, alpha/ gamma ratio, and slow potentials (i.e., the CNV)	GSR and self-reported peak experiences
Hatfield et al. (2013)	high and low pressure conditions	19 ROTC student volunteers	within-subject	performed 40 shots using the Noptel Shooter Training System in two conditions, competitive (included time constraints and rewards/penalties) and non-competitive	alpha band ERD/ERS	movement kinematics, state anxiety, and cortisol levels
Hatfield et al. (1984, Study 1)	before and during shooting	17 elite-level shooters	within-subject	performed an air rifle shooting task	alpha band activity and EEG alpha asymmetry	
Hatfield et al. (1984, Study 2)	different tasks	15 collegiate shooters	within-subject	performed an air rifle shooting and two non-shooting tasks, a verbal-analytic task and a visuospatial task	alpha band activity and EEG alpha asymmetry	
Hatfield et al. (1987)	before and during shooting	15 expert marksmen	within-subject	performed self-paced 40 shots to a target	theta, alpha, and beta band activity	ECG

Hatta et al. (2009)	athletes and non-athletes	eight elite kendo players and eight non-athletes	between-subject	performed 70 trials each of a left and right hand grip task (i.e., squeezing a dynamometer)	movement-related cortical potentials, specifically the Bereitschaftspotential, the negative slope, and the motor potential	EMG from forearm extensor muscles
Haufler et al. (2000)	experts and novices as a between-subjects factor and different tasks as a within-subjects factor	15 elite shooters and 21 novice shooters	mixed-model	performed simulated rifle shooting, as well as visuo-spatial and verbal tasks	theta, low alpha, high alpha, beta, and gamma band activity	
Hillman et al. (2000)	good and poor performance	seven expert shooters	within-subject	performed simulated rifle shooting	alpha and beta band activity	
Holmes et al. (2006)	good and poor performance	six expert shooters	within-subject	performed a 40 shots (using the SCATT Shooter Training system) and three observation tasks	alpha band ERD/ERS	
Hung et al. (2008)	experts and novices	15 expert shooters and 21 novice shooters	between-subject	performed 40 shots in a standing position with a 5s aiming period	EEG dimensionality (i.e., D2)	
Hung et al. (2004)	experts and novices	15 highly skilled table tennis players; 15 non-athletic college students	between-subject	completed a cued reaction time task (i.e., Posner's cued attention task)	Slow potentials, including lateralized readiness potentials	
Hunt et al. (2013)	winning athletes and losing athletes	17 collegiate/ROTC volunteers	between-subject	performed 40 shots using the NOPTEL Shooter Training system in a head-to-head competition with another participant. Participants were assigned to either the 'winning' group (n=10) or 'losing' group (n=7) depending on whether they won or lost the competition	delta, theta, alpha, low alpha, high alpha, beta, and gamma band activity	self-reported confidence

(*Continued*)

Study	*Focus*	*Participants*	*Design*	*Task*	*EEG Variables*	*Other Variables*
Janelle et al. (2000)	experts and novices	12 expert shooters and 13 nonexpert shooters	between-subject	performed 40 shots in a standing position using the Noptel Shooter Training system	alpha and beta band activity	visual point of gaze (as an index of Quiet Eye duration)
Kao et al. (2013)	good and poor performance	18 skilled golfers	within-subject	performed 100 putts. Putts were divided into 15 best and 15 worst outcomes	frontal theta band activity	
Kerick et al. (2004)	pre- and post-training as a within-subjects factor and two different tasks as another within-subjects factor	11 novice pistol shooters	multi-factorial	performed a shooting and a postural simulation task at two different time periods (i.e., before and after a 12–14 week training period)	high alpha band activity	
Kerick et al. (2007)	different tasks	14 experienced shooters	within-subject	performed a simulated shooting task, involving decision (enemy/no-enemy) and no-decision conditions	theta and upper alpha band activity	perceived workload
Kerick et al. (2000)	different types of feedback	17 novice rifle shooters	within-subject	performed 40 shots in a seated position (with the rifle supported by a shooting stand) in four different conditions, including no-feedback (about performance), low feedback, moderate feedback, and high feedback	EEG alpha asymmetry	subjective performance (using the Subjective Performance Questionnaire) and affect (using the PANAS)
Kerick et al. (2001)	different tasks	eight skilled marksmen	within-subject	performed shooting, postural control, and movement control tasks	alpha band ERD/ERS	

Kim and Woo (2013)	disabled and non-disabled shooters	12 disabled air pistol shooters; 22 non-disabled elite shooters	between-subject	performed 20 self-paced shots using the SCATT Shooter Training system	alpha band activity and EEG alpha asymmetry (R-L)	
Kim et al. (2013)	disabled and non-disabled shooters	12 disabled air pistol shooters and 22 non-disabled elite shooters	between-subject	performed 20 self-paced shots using the SCATT Shooter Training system	theta, low alpha, high alpha, beta, and gamma band coherence	
Kita et al. (2001)	athletes and non-athletes	four kendo players, two gymnasts, and nine non-athletes	between-subject	performed brief, self-paced wrist extensions of the right hand	movement-related cortical potentials, specifically the Bereitschaftspotential, the negative slope, and the motor potential	EMG (from the right wrist extensor muscles)
Konttinen and Lyytinen (1992)	experts and novices as a between-subject factor and good and poor performance as a within-subjects factor	three skilled marksmen and three novice shooters	mixed-model	performed simulated rifle shooting	slow potentials	heart rate and respiration
Konttinen and Lyytinen (1993a)	good and poor performance	12 expert shooters	within-subject	performed simulated rifle shooting	slow potentials	heart rate and respiration
Konttinen and Lyytinen (1993b)	four tasks, varying with regard to motor and visual targeting requirements	eight novice shooters	within-subject	performed four different shooting tasks varying with regard to motor and visual components	slow potentials	rifle stability and heart rate and respiration
Konttinen et al. (2000)	experts and novices	six elite marksmen; six pre-elite marksmen	between-subject	performed simulated rifle shooting	slow potentials	
Konttinen et al. (1999)	experts and novices	six elite marksmen and six pre-elite marksmen	between-subject	performed simulated rifle shooting	slow potentials	body sway
Konttinen et al. (1995)	good and poor performance	six elite marksmen and six pre-elite marksmen	within-subject	performed simulated rifle shooting	slow potentials	

(*Continued*)

Study	*Focus*	*Participants*	*Design*	*Task*	*EEG Variables*	*Other Variables*
Konttinen et al. (1998)	experts and novices	six elite marksmen and six pre-elite marksmen	between-subject	performed simulated rifle shooting	slow potentials	
Landers et al. (1994)	pre- and post-training as a within-subjects factor	11 novice archers	within-subject	performed an archery shooting task at two different time periods (i.e., before and after a 15-w archery training class)	4–30 Hz activity	
Loze et al. (2001)	good and poor performance	six expert air-pistol shooters	within-subject	performed a shooting task	alpha band activity	
Luchsinger et al. (2016)	athletes and non-athletes as a between-subjects factor and resting and post-exercise performance as a within-subject factor	nine biathletes and eight non-athletes	mixed-model	performed 100 shots using the SCATT Shooter Training System in two conditions, resting and post-exercise (i.e., five-minute inline skating)	frontal theta band activity	perceived exertion (using a Borg scale) and self-reported concentration (using a visual analogue scale)
Mann et al. (2011)	experts and novices as a between-subject factor and good and poor performance as a within-subjects factor	10 expert golfers and 10 near-expert golfers	mixed-model	performed two blocks of 45 putts each	movement-related cortical potentials, specifically the Bereitschaftspotential	Quiet Eye duration and EMG from right forearm extensor muscles
Martin et al. (1993)	athletes and non-athletes	24 tennis players, 24 rowers, and 24 non-athletes	between-subject	completed a period of monaural stimulation (i.e., listening to 'clicks' presented to right and left ears)	brainstem auditory evoked potentials	
Nakamoto and Mori (2008)	athletes and non-athletes	nine college baseball players and nine college non-baseball players	between-subject	performed an anticipation timing (Go/Nogo) reaction time task with varying levels of stimulus response compatibility (i.e., compatible with baseball batting and not compatible with baseball batting)	movement-related cortical potentials, specifically the CNV	

Nakamoto and Mori (2012)	experts and novices	seven expert baseball players and seven novice baseball players	between-subject	performed an anticipation timing (Go/Nogo) reaction time task in two conditions, timing unchanged and timing unexpectedly changed	movement-related cortical potentials, specifically the CNV	
Radlo et al. (2001)	experts and novices	10 advanced baseball players and 10 intermediate-level baseball players	between-subject	completed a baseball pitch discrimination task	P300	reaction time
Radlo et al. (2002)	internal and external attentional focus strategy	20 novice dart throwers	between-subject	performed 10 blocks of four dart throws in one of two conditions. Dart throws were performed either using an internal attention focusing strategy or using an external attention focusing strategy	alpha power	heart rate and EMG activity
Reinecke et al. (2011)	different tasks	11 collegiate golfers	within-subject	performed self-paced putts in two conditions, inside and outside	theta, alpha1, alpha2, and beta1 band activity	state anxiety (using the STAI)
Rietschel et al. (2011)	good and poor performance	13 college student volunteers	within-subject	completed 60 trials of a visuomotor pointing task in two conditions, performing alone and performing with social evaluation (i.e., two confederates standing just behind the participant)	low alpha, high alpha, and gamma band coherence	heart rate and skin conductance
Rossi and Zani (1991)	different tasks	four skilled skeet-shooters and four skilled trap-shooters	within-subject	performed an auditory discrimination task with two levels of difficulty, easy and difficult	including the N2 and P300 waveforms	reaction time

(*Continued*)

Study	*Focus*	*Participants*	*Design*	*Task*	*EEG Variables*	*Other Variables*
Rossi et al. (1992)	athletes and nonathlates as a between-subjects factor and easy and difficult tasks as a within-subjects factor	11 expert fencers and 10 non-athletes	mixed-model	performed an auditory discrimination (Go/NoGo) reaction time task with two levels, easy and difficult	including the N2 and P300 waveforms	reaction time
Salazar et al. (1990)	different tasks as one within-subjects factor and good and poor performance as another within-subjects factor	13 male and 15 female archers	multi-factorial	performed four tasks, including shooting with normal bow; shooting with light bow; bow drawing without aiming; and aiming without bow drawing	5–31 Hz activity	
Shelley-Tremblay et al. (2006)	high and low pressure conditions	20 novice golfers	within-subject	performed 20 putts with and without an audience	alpha, beta1, and beta2 band activity	mood states (using the Profile of Mood States)
Stikic et al. (2014, Study 1)	before and during shooting	51 adult volunteers (i.e., volunteers without any marksmanship training)	within-subject	performed a simulated shooting task using the Virtual Battle Space2 Tactical Warfare Simulator	self-organizing neural networks;	
Stikic et al. (2014, Study 2)	before and during shooting	11 experienced golfers and 11 novice golfers	within-subject	performed 10 sessions of 10 putts each	self-organizing neural networks;	
Taddei et al. (2012)	athletes and non-athletes	10 older fencers, 10 younger fencers, 10 older non-athletes, and 10 younger non-athletes	between-subject	performed a simple reaction time task and a discrimination (Go/NoGo) reaction time task	including the P1, N1, P2, N2, and P300 waveforms	
Taddei et al. (1991)	athletes and non-athletes	eight expert fencers and eight non-athletes	between-subject	completed a period of visual stimulation (i.e., watching an alternating checkerboard pattern) in two conditions, large visual field and small visual field	visual evoked potentials, including the P60-N75, N75-P100, and P100-N145 waveforms	

Taliep and John (2014)	experts and novices	eight skilled and 10 less skilled cricket batsmen	between-subject	watched 24 bowling deliveries and decided whether they were in-swinger or out-swinger deliveries	alpha band event-related desynchronization	reaction times
Thomas and Mitchell (1996)	athletes and non-athletes	10 endurance runners, seven elite gymnasts, and seven non-athletes	between-subject	completed a period of somatosensory stimulation (using a Nihon Kohden Electromyograph with stimulating electrodes attached to the wrist)	somatosensory evoked potentials, including the P9, P11, P13/14, N20, P25, and N30 waveforms	reaction time
Thomas et al. (2005)	athletes and non-athletes	25 elite cricketers and 10 non-athletes	between-subject	completed a period of visual stimulation (i.e., watching an alternating checkerboard pattern)	visual evoked potentials including the N70, P100, and N145 waveforms	choice reaction time
Twigg et al. (2014)	before and during shooting	two experienced archers	within-subject	shot 12 arrows	1–30 Hz activity	
Velikova et al. (2012)	eyes open versus eyes closed conditions	13 expert fencers	within-subject	completed several different conditions, including maintaining eyes open, maintaining eyes closed, making in-phase movements, and making anti-phase movements	delta, theta, alpha2, alpha2, beta1, beta2, beta3, and gamma band coherence	
Vrbik et al. (2015)	good and poor performance	four experienced, recurve bow archers and four experienced, compound bow archers	within-subject	shot 12 arrows	attention’ and ‘meditation’ scores (i.e., as derived from Mindwave Mobile Software algorithms)	HRV
Wang et al. (2015)	experts and novices	12 experienced badminton players and 13 non-athletes	between-subject	performed visuo-spatial attention and working memory tasks	theta, alpha, and beta band activity	self-reported physical activity
Wolf et al. (2014)	different levels of expertise	14 expert table tennis players, 15 amateur table tennis players, and 15 young elite table tennis players	between-subject	watched 40 videos of table tennis strokes and were asked to imagined themselves responding to the strokes	SMR band ERD/ERS	

(*Continued*)

Study	*Focus*	*Participants*	*Design*	*Task*	*EEG Variables*	*Other Variables*
Wolf et al. (2015)	experts and novices	14 expert table tennis players and 15 amateur table tennis players	between-subject	watched 40 videos of table tennis strokes and imagined themselves responding to the strokes	EEG alpha asymmetry and theta band coherence	
Wu et al. (2007)	good and poor performance	12 highly skilled basketball players	within-subject	shot 50 baskets	low alpha, high alpha, and low beta band coherence	
Zhu et al. (2011, Study 1)	high reinvestment/self-monitoring and low reinvestment/self-monitoring athletes	16 novice golfers	between-subject	performed a putting task	alpha1 and alpha2 band coherence	self-reported movement self-monitoring
Zhu et al. (2011, Study 2)	implicit and explicit practice	18 novice golfers randomly assigned to implicit and explicit practice conditions	between-subject	performed a putting task	alpha1 and alpha2 band coherence	
Ziółkowski et al. (2014)	athletes and non-athletes	36 amateur boxers and 52 college student volunteers	between-subject	completed three one-minute periods, including maintaining eyes open, maintaining eyes closed, and maintaining visual focus	delta, theta, alpha, SMR, beta, and high beta band activity	