

COGNITIVE FLEXIBILITY, INTERHEMISPHERIC TRANSFER, AND QEEG IN  
CONCUSSED FEMALE ATHLETES

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**Cognitive Flexibility, Interhemispheric Transfer, and QEEG in Concussed Female Athletes**

For over a decade, sports-related concussions, a form of mild traumatic brain injury (mTBI), have been a major focus of research in the fields of medicine, athletic training, and psychology. Research in this area is especially important because of the increasing incidence of sports-related concussions. The Centers for Disease Control and Prevention (CDCP) (2010) estimate that over 300,000 sports-related traumatic brain injuries occur each year in the United States alone, and sports-related concussions are “second only to motor vehicle crashes as the leading cause of traumatic brain injury” (p. 495).

For the purposes of their study for the National Collegiate Athletic Association (NCAA), McCrea et al. (2003) defined a concussion as “an injury resulting from a blow to the head causing an alteration in mental status and 1 or more symptoms prescribed by the National Academy of Neurology Guideline for the Management of Sports Concussion” (p. 2558).

**Commonly Reported Symptoms of Concussion**

Although every concussion is different, the most common symptoms include “headache, nausea, vomiting, dizziness/balance problems, fatigue, difficulty sleeping, drowsiness, sensitivity to light or noise, blurred vision, memory difficulty, and difficulty concentrating” (McCrea et al., 2003, p. 2558). Most symptoms generally subside within one to two weeks, and athletes are permitted to return to play (Macciocchi, Barth, Littlefield, & Cantu, 2001, McCrea et al., 2003). However, Moser (2007) notes that headache, dizziness and symptoms of irritability and depression could last for up to six weeks post-injury, and other recent research suggests that neurological and neurocognitive deficits associated with concussion are much longer lasting.

### **Neurological Consequences of Concussion**

**Early neurological problems.** In terms of neurological damage, concussions tend to result in diffuse damage. Damage is most often caused by acceleration, deceleration, and rotation of the head upon impact (Willberger, Ortega, & Slobounov, 2006). This can cause contusions in the frontal and temporal lobes and brain swelling that can tear and shear axons, destroying neural connections in the brain (Thatcher, 2006; Freeman, Barth, Broshek, & Plehn; Moser, 2007).

Past research also suggests that the corpus callosum, the band of axons that connects the two hemispheres of the brain, is one of the areas more susceptible to concussion-related damage (Hammond-Tooke, Goei, du Plessis, & Franz, 2010; Nishimoto & Murakami, 1998). Hammond-Tooke and colleagues used a bimanual reaction time task to determine whether damage to the corpus callosum was present in participants who had sustained mild concussions (2010). The differences they found between control and concussed participants disappeared in a second trial one month post-injury, however it is possible that a more complex interhemispheric transfer task may be able to detect differences in corpus callosum functioning.

**Second impact syndrome.** Another major concern following a concussion is second impact syndrome (SIS), a condition that occurs when an athlete sustains a head injury while still recovering from a previous concussion. This is especially troubling because sustaining one concussion puts athletes at greater risk for sustaining additional concussions in the same season; Guskiewicz, Weaver, Padua, & Garrett (2000) report that high school football players who sustain one concussion are as much as three times more likely to sustain an additional concussion. They suspect that this is because concussed athletes are permitted to return to play too quickly and without neurological and neuropsychological assessment.

Even when the second injury is less severe than the first, SIS can cause serious damage and massive brain swelling (Theye & Mueller, 2004). It is extremely dangerous to return to athletic activities while still recovering from a concussion because brain swelling can also cause intracranial pressure, confusion, collapse, and death (Freeman et al., 2005).

Due to the serious neurological consequences associated with sports-related concussion, additional understanding of the interim and long-term impact of concussions is needed to inform preventative education and long-term treatment for concussions.

**Interim and long-term neurological issues.** There is a wealth of research on the consequences of sports-related concussion in the days, weeks, and months following injury including the potential for second impact syndrome. However, when symptoms of concussion or concussion-related deficits do not resolve in the weeks after injury, the injured athlete can be diagnosed with post-concussion syndrome. Research suggests that deficits that result from concussions are cumulative in nature, and with each additional concussion sustained, damage and cognitive deficits worsen. In recent years, research has also linked repeated concussions to neurological abnormalities and cognitive problems much later in life, years after an injury occurs.

McCrea, Pritchep, Powell, Chabot, and Barr (2010) speak to the utility of electrophysiological technology for the study of concussions, stating that, “there is a window of cerebral vulnerability that may extend beyond the point at which full clinical recovery has been observed,” and EEG is one way of examining this (2010, p. 284). In essence, electrophysiological technology can detect abnormalities that may explain lingering neurocognitive impairments, even after other neurological symptoms resolve (Hughes & John, 1999).

One study used event related potentials (ERPs), an electrophysiological measure of response to stimuli, to examine neural functioning of athletes who had sustained multiple concussions as compared with athletes who had sustained zero, one or two concussions (Gaetz, Goodman, & Weinberg, 2000). None of the participants had sustained concussions in the past six months, and most participants had not sustained a concussion in over a year. Results showed electrophysiological differences in athletes who had experienced multiple concussions when they were asked to categorize target and non-target stimuli. This study provides evidence of lasting neurological differences in athletes who sustain multiple concussions.

Recent research has also examined neural functioning in retired university athletes between the ages of fifty and sixty-five (DeBeaumont et al., 2009). Although athletes with a history of sports-related concussion and athletes with no concussion history did not differ significantly from one another in terms of reaction time or response accuracy, their electrophysiological recordings suggest that retired athletes who had experienced concussions engaged in more effortful processing than control group participants.

In addition, repeated sports-related concussions and other traumatic brain injuries can also eventually cause epileptic seizures, and they put athletes at greater risk for developing mild cognitive impairment (MCI), Alzheimer's disease, Parkinson's disease, and other brain disorders, including chronic traumatic brain injury (CTBI) or chronic traumatic encephalopathy (CTE) (CDCP, 2010; Guskiewicz et al., 2003). CTE is especially concerning because of its rapid progression after onset. It generally begins with mild confusion and can progress to serious symptoms of dementia as soon as ten to thirty years after an athlete retires from sports (Erlanger et al., 1999; Jordan, 2000). Neuropathologically, CTE is characterized by atrophy in the

cerebrum and Alzheimer's-like neurofibrillary tangles in the limbic system and substantia nigra (Erlanger et al., 1999).

**Tracking neurological damage.** Unfortunately, concussion-related damage is difficult to examine using current neuroimaging techniques. For example, Elleberg et al. (2009) reported that computed tomography (CT) scans are most often negative for lesions and that magnetic resonance imaging (MRI) can only sometimes detect small contusions, hematomas, and hemorrhages in those who have sustained a concussion.

However, as mentioned previously, electrophysiological methods such as resting electroencephalograms (EEG) are especially effective in concussion research. Quantitative EEG (QEEG) and event related potentials (ERPs), in particular, are considered more sensitive to diffuse damage than structural imaging methods (Thatcher, Walker, Gerson, & Geisler, 1989; Gaetz, Goodman, & Weinberg, 2000; Elleberg et al., 2009). This makes them ideal to study issues with post-concussion neural firing and predict recovery outcomes (Thatcher et al., 1989).

Research suggests that QEEG in particular is especially effective for identifying neural dysfunction associated with post-concussion syndrome, as indicated by “increased focal or diffuse theta, [and] decreased alpha” (Hughes & John, 1999, p. 198). QEEG technology digitizes brain signals, so they can be analyzed mathematically. Using QEEG, researchers can analyze the strength of brainwaves at different frequencies (i.e. theta, alpha, beta, gamma) (Thornton & Carmody, 2008). ERPs, on the other hand, measure the timing of neural responses to stimuli (Ray & Slobounov, 2006). Elleberg et al. (2009) reported that even when athletes do not report symptoms of a concussion, ERPs show deficits, especially when the athlete has sustained more than three concussions in the past. These ERP deficits indicate that athletes who sustain concussions use more mental energy to complete difficult tasks.

In studies that utilize EEG technology, the frequency bands most often associated with concussion-related abnormalities are theta, alpha, beta, and gamma (For comprehensive reviews, see Thatcher, 2006; Thompson & Hagedorn, 2012). Theta activity refers to EEG activity between four and eight hertz (Hz) (Ray & Slobounov, 2006). It is associated with both alertness and attention, and theta activity is also observed when participants perform cognitive or perceptual tasks that require efficient processing (Ray & Slobounov, 2006). EEG activity in the range of eight to twelve Hz falls in the alpha band, associated with “relaxation and lack of active cognitive processes” (2006, p. 224). Beta activity refers to EEG activity in the range of eighteen to thirty Hz. It is associated with alertness (Ray & Slobounov, 2006). Gamma activity refers to EEG activity between thirty and seventy Hz, and it is most commonly associated with integrating parts into a whole (Ray & Slobounov, 2006).

In general, when concussion-related abnormality exists, EEG recordings show lower amplitude in the alpha, beta, and gamma frequencies (Thatcher, 2006). Thompson and Hagedorn (2012) state that there also tends to be less power in the faster wave frequencies (e.g., beta) and an increase in the prevalence of slower waveforms (e.g., theta).

In their landmark study on EEG and mild head trauma, Thatcher et al. (1989) examined EEG recordings of over 600 mostly male inpatients and outpatients with mild head injuries and over 100 age-matched controls. The participants in the head injury group had sustained head injuries anywhere from seven days to eight years prior to participation in the study, but on average, EEG recording took place about eight days after the injury. Their EEG recordings showed an overall decrease in alpha power particularly in the posterior cortex.

McCrea et al. (2010) recorded baseline resting neural activity and neural activity at varying intervals post-concussion (on the day of injury, eight days post-injury, and forty-five

days post-injury). They compared neural activity for delta, theta, alpha, beta, and gamma frequency bands of the concussed athletes to neural activity of matched control subjects. Results indicated that for the beta frequency band, concussed athletes exhibited increased power on the day of injury and at eight days post-injury (McCrea et al., 2010).

### **Neurocognitive Deficits Associated with Concussion**

**Early neurocognitive deficits.** Neurocognitive tests are often used to pinpoint specific concussion-related cognitive deficits. Memory, executive functioning, processing speed, and attention are four specific areas of functioning often tested post-concussion.

Although concussed athletes often report difficulty with memory in the days and weeks immediately following a concussion, research suggests that memory deficits lessen as time progresses. In their study of concussed and control female soccer players six to eight months post-concussion, Elleberg, Leclerc, Couture, and Daigle (2007) found no significant deficit in memory as measured by the California Verbal Learning Test (CVLT immediate and delayed memory) and a basic digit span task. The Elleberg et al. (2007) study is also unique because it is one of the only concussion studies that focuses exclusively on female athletes.

Similarly, results of past research on executive functioning of concussed athletes has shown no significant evidence of deficits in performance on the Controlled Oral Word Association (COWA) test, a test of verbal fluency, or the Tower of London task, a test of planning (Ravdin, Barr, Jordan, Lathan, & Relikin, 2003; Elleberg et al., 2007). Although concussed athletes did not exhibit deficits in planning moves for the Tower of London task, Elleberg et al. (2007) noted that they took significantly longer to plan their moves and took significantly more steps to complete the task than control athletes. This is evidence of possible processing speed deficits associated with concussion.

Other research on neurocognitive deficits associated with concussion examines cognitive flexibility in terms of divided attention and response inhibition. Bruce and Echemendia (2003) and Ellemberg et al. (2007) used versions of the Stroop test to determine whether concussed athletes had deficits in working memory and attention. Bruce and Echemendia (2003) found no significant differences in performance on the color-word version of the Stroop test (Trennery, Crosson, DeBoe, & Leber, 1989) between concussed and control athletes. Ellemberg et al. (2007) created an alternate version of the Stroop test which included an attentional inhibition task and an attentional flexibility task. The inhibition task required participants to name the color that a series of color words were printed in. The cognitive flexibility task required subjects to switch between tasks, reading color words that were surrounded by a rectangle and naming the color of color words that were not surrounded by a rectangle. Ellemberg and colleagues found that the concussed female participants exhibited significant deficits in both cognitive inhibition and flexibility as compared to the control group. Concussed female athletes took significantly longer on both the inhibition task and the cognitive flexibility task.

**Interim and long-term neurocognitive deficits.** Because research suggests sports-related concussions may be an antecedent to serious cognitive problems later in life, some researchers have begun to examine whether cognitive deficits also exist in the interim period, months after symptoms like headache, nausea, dizziness, and fatigue subside.

Gardner, Shores, and Batchelor (2010), for example, tested rugby players five months to five years after injury. Results suggested that rugby players with a history of repeated concussion had significantly slower processing speed scores on the Wechsler Adult Intelligence Scale – 3rd Edition (WAIS-III) as compared to athletes with no concussion history. This result echoes the results of the Ellemberg et al. (2007) study, which suggested that six to eight months

post-injury, concussed female athletes took significantly longer than control athletes to complete the Stroop and Tower of London tasks. Additional research is required to determine the nature of this deficit in the interim period.

According to the CDCP (2010), repeated concussions have also been found to cause lasting deficits in memory, reasoning, and vision, and they can also temporarily alter personality or cause anxiety and aggressive behavior. In terms of long-term memory deficits, research suggests that retired athletes who have sustained three or more concussions are five times more likely to be diagnosed with MCI and three times more likely to report significant memory problems (Guskiewicz et al., 2005). DeBeaumont et al. (2009) found that even thirty years following a concussion, former athletes exhibited deficits in episodic memory, as well as motor slowness. According to a review of the CTE literature by Costanza and colleagues, athletes who develop CTE often struggle with memory, attention, concentration, information processing, executive functioning, cognitive flexibility and spatial abilities (2011).

### **Concussion and Gender**

Results of recent research have also indicated that concussion prevalence is different for male and female athletes. This difference could be the result of both socially constructed gender differences and biological sex differences influencing aggressive play. Covassin, Swanik, and Sachs (2003) reported the incidence of sports-related concussions for male and female athletes based on number of concussions per athlete exposure, which they defined as every time an athlete participates in a practice or game where he or she is exposed to the chance of injury. They reported that the incidence of concussions for males was 0.6 for every 1,000 athlete exposures (AE). For females, the incidence of concussion was slightly lower, 0.4 for every 1,000 AEs.

Covassin et al. (2003) also reported that female athletes were more likely to sustain concussions during games, whereas males were more likely to suffer concussions during sports practices. Covassin and colleagues noted that these differences may suggest that female athletes practice at a lower intensity level relative to their game level intensity, and McKeever and Schatz (2003) concluded that male athletes participated in more risky behavior in sports. Although both male and female soccer players sustained concussions primarily from heading the ball and goalkeeping, female athletes were more likely to sustain a concussion after contact with the ball or with the ground, whereas males were found to sustain concussions from physical person-to-person contact (Gessel et al., 2007). Considering possible biological influences on sex related difference in incidence sports-related TBI, Gessel et al. (2007) noted that females may sustain more concussions because they have a smaller head to ball ratio, and their necks accelerate faster because they have weaker neck muscles.

The vast majority of concussion research (e.g., Bruce & Echemendia, 2003; Ravdin et al., 2003; Gardner et al., 2010) examines mainly collegiate and professional level male athletes because incidence of concussion is higher for this group (Gessel et al., 2007). The Ellemberg et al. (2007) study appears to be one of the only concussion studies that focuses exclusively on female athletes. Because there are noted gender differences in both incidence of concussion and the manner by which concussions are sustained (Covassin et al., 2003; McKeever & Schatz, 2003; Gessel et al., 2007), additional research on deficits associated with concussion is needed for female athletes throughout the lifespan.

Although there is a wealth of research on sports-related concussion in male athletes in the hours, days, weeks and months immediately following injury as well as functioning of retired athletes thirty or more years after injury, there is little research about concussed individuals'

functioning in the interim and virtually no research focused on concussed female athletes for this time frame.

We used QEEG technology in conjunction with two additional measures to determine whether abnormalities in neural firing or deficits in cognitive flexibility or interhemispheric transfer time (IHTT) exist for female athletes who have experienced concussions six months to ten years prior to testing. We expected that female athletes with a history of one or more concussions in the past ten years would display deficits in processing speed on tests of cognitive flexibility and IHTT as well as abnormalities in neural firing, particularly with respect to theta, alpha, beta, and gamma frequency bands as compared to athletes who have never sustained a concussion. Thus, when results from a Stroop switching task, an interhemispheric transfer task, and data from four EEG frequency bands are used as predictors of concussion status in a discriminant function analysis (DFA), they should adequately distinguish between control participants and participants who have sustained sports-related concussions in the past.

## **Method**

### **Participants**

Because part of the purpose of this study is to fill the gap in the concussion related literature with research on concussion-related deficits and neuronal firing differences in females, only female athletes at Ball State University who had been involved in an organized sport in the past year were recruited. The other major purpose of this research was to examine concussion-related neurological and cognitive issues in the interim period (at least six months post-injury); thus, only participants who had not sustained a concussion in the past six months were recruited.

Because individuals who are predominantly left-handed can show differences in neural firing patterns in electroencephalography (EEG) recordings and process information differently,

only right-handed participants were recruited. Finally, participants were excluded from the study if they indicated a history of neurological problems or past diagnosis of attentional disorders. These could mimic concussion-related problems on the interhemispheric transfer task and the Stroop task and impact neural firing rates recorded using EEG.

Participants were forty-six female student athletes recruited through the introductory psychology student subject pool, campus-wide emails, and through other participants. Eighteen participants were excluded from primary data analysis because of missing data. Nineteen of the original forty-six participants received research credit for their introductory psychology course, and twenty-seven participants who were not enrolled in an introductory psychology course received monetary compensation for participating.

Although we originally intended to examine differences between athletes who had no concussion history, athletes who had a history of one or two concussions, and athletes who had a history of multiple concussions using a three group design similar to the grouping used by Gaetz and colleagues (2000), we were unable to do so because only seven participants with a history of multiple concussions completed the study with no missing data, and complete data and relatively equal groups were required for our chosen analysis.

For the primary analysis, fourteen participants who reported no history of concussions comprised the control group ( $M$  age = 20.04,  $SD$  = 0.99), and fourteen participants who reported a history of one or more concussions comprised the experimental group ( $M$  age = 20.40,  $SD$  = 1.16;  $M$  number of concussions = 1.86,  $SD$  = 1.17;  $M$  months since last concussion = 33.57,  $SD$  = 19.55).

For the purposes of follow-up testing, all cases were analyzed. Twenty-six participants made up the control group ( $M$  age = 19.96,  $SD$  = 1.19), and twenty participants comprised the

concussion group ( $M$  age = 20.47,  $SD$  = 1.51;  $M$  number of concussions = 1.85,  $SD$  = 1.14;  $M$  months since last concussion = 33.07,  $SD$  = 25.73).

## Measures

Participants completed a health survey and the Edinburgh Handedness Inventory (Oldfield, 1971). They underwent five minutes of QEEG recording, and completed an interhemispheric transfer task and a Stroop task. It took no more than one hour for each participant to complete the measures.

**Health survey.** Participants completed a brief health survey, made up of seven questions regarding past medical history (Figure 3). Participants responded to questions regarding athletic history, concussion history, medical/neurological history, and attentional disorder diagnosis. This survey was used to divide participants into groups for the analyses and exclude participants who had a history of neurological problems or attentional disorders that could impact neural functioning or mimic concussion-related deficits on the interhemispheric transfer task or the Stroop task.

**Edinburgh Handedness Inventory (Oldfield, 1971).** Participants then completed the Edinburgh Handedness Inventory, a brief measure on which participants indicate which hand they generally use to complete a variety of common tasks (Figure 4). Participants check two boxes for each prompt. If a participant uses primarily her right hand to complete a task, she puts two checks in the right hand column, but if the participant uses either hand to complete the task, she puts one checkmark in each column. This inventory was used to exclude participants who were predominantly left handed from participating because they could show differences in neural firing patterns in EEG recordings.

**Cognitive flexibility.** Results of past research are still unclear as to whether deficits in cognitive inhibition and flexibility exist in athletes who have sustained concussions (Bruce & Echemendia, 2003; ElleMBERG et al., 2007). In order to determine whether lasting deficits in cognitive flexibility exist in athletes who have sustained concussions in the past, we used a test of cognitive flexibility as a predictor variable in our analysis.

The Stroop (1935) test, is a popular measure of attentional interference; however alternate versions of the task involve cognitive flexibility as participants are required to switch between rules. In a standard Stroop task, participants read a list of color words, name the color of a series of colored X's, and then name the color that a series of color words are printed in. For the purposes of this study, we used an alternate version of the Stroop test which included a cognitive flexibility subtask. The version of this task we used was very similar to the one used by ElleMBERG and colleagues (2007).

This version of the Stroop test has four major subtasks (Figure 5). For the first subtask, participants named the color of each of a series of boxes. For the second subtask, participants read a series of color words (red, blue, green, yellow). Although these brief subtasks were not included in analyses, they were important because they were used to exclude participants for difficulty reading or perceiving colors. Considerable difficulty with reading simple color words or identifying colors would artificially depress scores on the switching subtask score. The third subtask is an attentional inhibition task which requires the participant to name the color that a series of color words are printed in. This subtask served to familiarize participants with what they would need to do to complete the fourth subtask. The fourth subtask requires cognitive flexibility, as participants are required to switch between tasks. They must read color words that

are surrounded by a rectangle but name the color of color words that are not surrounded by a rectangle.

Researchers noted any difficulties participants had with the first three tasks, but only the fourth subtask was scored and analyzed for the purposes of this study. Participants received feedback on their performance on each item, and were not allowed to advance to the next item until they responded correctly. We recorded the total time it took each participant to complete the switching task as well as number of errors and self-corrected errors. Stroop switching task completion time was used as a predictor variable in the analysis.

**IHTT task.** Because past research suggests the corpus callosum, the structure involved in interhemispheric transfer, is especially susceptible to concussion-related damage, we used a computerized task based on the Poffenberger paradigm to determine whether concussed athletes show differences in IHTT after the initial recovery period (Hammond-Tooke et al., 2010; Marzi, 1999; Nishimoto & Murakami, 1998; Westerhausen et al., 2006). This task was administered using E-Prime software.

Participants fixated on a cross in the middle of the computer screen and responded to a target symbol that flashed in their left or right visual field. Participants completed one practice block with each hand. Then they completed four additional blocks, two with each hand. For the first and third blocks, participants responded using their right index finger, and for the second and fourth trials, they responded using their left index finger. Theoretically, because the right side of the body is controlled by the left side of the brain (and vice versa), it should take longer for all participants to respond to the target symbol when they are required to respond with the hand opposite of the visual field where the target symbol flashes (Figure 6). We hypothesized that this effect would be more pronounced for participants who had sustained concussions

because of the probability of axonal damage in the corpus callosum, so we included IHTT as a predictor variable in the analysis.

Due to low accuracy rates on our originally programmed IHT task, we revised the task midway through data collection to include catch trials. Twenty participants completed the older version of the IHT task which was more difficult and did not include catch trials, and sixteen participants completed the revised version of the IHT task which included catch trials. We calculated IHTT for both versions of the task and found no significant difference in IHTT,  $t(36) = -0.67, p > 0.05$ . However, as intended, participants were significantly more accurate on the new version of the task,  $t(36) = 12.83, p < 0.05$ . Nonetheless, the pattern of results was similar for both versions of the task. Because only using data from participants who completed the new version would significantly limit the number of usable cases for the analysis, all IHT task data was grouped together and used as one predictor variable in the analysis.

**EEG recording.** To determine whether abnormalities at the neural level exist in athletes at least six months after concussion, we followed a procedure similar to that used by McCrea et al. (2010). All participants underwent five minutes of eyes open resting EEG recording using NeuroGuide. Although McCrea and colleagues used ten minutes of eyes open resting EEG recording, past experience in our lab has shown at least sixty seconds of artifact-free data can be obtained from a five minute recording.

Data were collected using a cloth cap with nineteen electrodes referenced to electrode A1 and later re-referenced offline to average ears for analysis. Although using fewer electrodes makes it more difficult for QEEG to detect problems, Thatcher (2006) reports that using even two to five channels proves sensitive enough to differentiate between control participants from participants with brain injuries.

Artifacts from eye movement and muscle tension were removed via an algorithm programmed into the NeuroGuide software and through experimenter data inspection. Because past research has found significant differences in frequency band power between control and concussed participants (Hughes & John, 1999; McCrea et al., 2010; Thatcher, 2006; Thompson & Hagedorn, 2012), we analyzed average spectral power (ASP) for theta, alpha, beta, and gamma frequency bands. Left hemisphere and right hemisphere readings for each frequency band were highly correlated, so whole head QEEG readings for each frequency band were used as predictors in the primary analysis. Epoch length for control participants ( $M = 178.84$  seconds,  $SD = 62.62$ ) was not significantly different from average epoch length for concussion participants ( $M = 165.75$  seconds,  $SD = 42.40$ ),  $t(26) = 0.65$ ,  $p > 0.05$ .

### **Procedure**

Because of the individual nature of the measures used in this study, participants were tested one at a time. First, a researcher instructed the participants to read and sign an informed consent document (Figures 1 and 2). Next, participants completed the survey measures previously described: the health survey and the Edinburgh Handedness Inventory (Oldfield, 1971).

Then, participants began the experimental procedure. First, participants underwent the QEEG recording. Two researchers placed a cloth cap with electrodes on the participant's head and inserted clear, room temperature gel into each electrode. If necessary, researchers also cleaned the participant's earlobes with a rough sponge to ensure good impedance readings from the linked ear reference points. The researchers then asked participants to sit quietly with their eyes relaxed, open and look towards a point on the floor for five minutes to minimize blinking. Finally, all participants completed the IHTT task and the Stroop task.

## Results

To determine whether differences in cognitive flexibility, IHTT, and neural firing patterns were important enough to differentiate between participants who had never sustained a concussion and participants who had experienced a concussion or concussions in the past, we used a discriminant function analysis (DFA). This analysis is used to predict participants' group membership from a set of predictors; DFA provides information regarding the statistical significance of the prediction, the adequacy of the classification, and the relative importance of the predictor variables (Tabachnick & Fidell, 2001).

Assumptions for DFA were adequately met. The control and concussion groups had an equal number of participants. Based on visual analysis of histograms (Figure 7), data for the predictor variables (Stroop switching task completion time, IHTT, and power for theta, alpha, beta and gamma EEG frequency bands) followed a roughly normal distribution. Visual analysis of scatter plots for each predictor variable also suggests that the assumption of linearity was adequately met (Figure 8). Box's Test of Equality of Covariance Matrices indicated that the homogeneity of variance-covariance matrices was adequately met (Box's  $M = 58.51$ ,  $p > 0.001$ ). Only four predictor variables had outliers over two standard deviations from the mean (Stroop switching task completion time, theta, alpha, and beta) (Figure 7), and there were no major issues with multicollinearity (i.e., high correlations between predictor variables) among the EEG frequency bands (Table 1), so we opted to proceed with the DFA.

The DFA demonstrated that Stroop switching task completion time, IHTT, and power for theta, alpha, beta and gamma EEG frequency bands did not significantly differentiate control participants from participants who had experienced concussions in the past,  $\Lambda(6, 28) = 0.729$ ,  $p > 0.05$ . Although the result of the DFA was not significant, the predictor variables accounted for

27.1% of the variance. The Structure Matrix indicated that Stroop switching task completion time and theta frequency power were most represented in the function (0.66, 0.57), and canonical discriminant function coefficients (0.06, 0.08) indicated that Stroop switching completion time and theta contributed most to group separation. In addition, 69.7% of cases were correctly classified as control or concussion group participants.

Because these two variables were identified as relatively important in the DFA, we examined cognitive flexibility and theta further using follow-up tests on all valid data. Because complete data for each participant was necessary for the primary analysis, eighteen participants who had missing data due to equipment malfunctions were not included in the DFA. Because follow-up tests examined only one variable at a time, we were able to run analyses on cases with missing data.

For the purposes of the follow-up independent samples *t*-test on Stroop switching task completion time, twenty-one participants composed the control group, and eighteen participants composed the concussion group. Differences between Stroop switching completion time for control ( $M = 63.00$ ,  $SD = 13.04$ ) and concussed participants ( $M = 57.96$ ,  $SD = 14.07$ ) were not significant,  $t(39) = 1.16$ ,  $p > 0.05$ . However, because means for the Stroop switching task were not in the predicted direction, we used a second independent samples *t*-test to examine the Stroop inhibition subtask. Differences for Stroop inhibition completion time for control ( $M = 7.86$ ,  $SD = 1.27$ ) and concussed participants ( $M = 8.58$ ,  $SD = 1.79$ ), were not significant,  $t(39) = 1.47$ ,  $p > 0.05$ .

For the follow-up analysis on theta power, eighteen participants composed the control group, and eighteen participants composed the concussion group. In the primary analysis, the DFA, theta was analyzed for the whole head because analyzing left and right hemispheres

separately would cause issues with multicollinearity. However, because left and right hemispheres are known to differ functionally, theta for each hemisphere was analyzed separately for follow-up testing. We used a factorial ANOVA to examine differences in theta power for concussion group and hemisphere. There was no significant interaction between theta hemisphere and concussion group,  $F(1, 36) = 1.12, p > 0.05$ . However, there was a main effect for concussion group,  $F(1, 36) = 4.24, p < 0.05$ , indicating control participants had significantly greater theta average spectral power (ASP) ( $M = 21.42, SD = 12.75$ ) than concussed participants ( $M = 14.44, SD = 6.06$ ). There was also a main effect for theta hemisphere,  $F(1, 36) = 4.19, p < 0.05$ , indicating that there was significantly larger theta ASP in the right hemisphere ( $M = 17.75, SD = 10.57$ ) than in the left hemisphere ( $M = 17.00, SD = 10.32$ ).

### **Discussion**

The purpose of this study was to determine whether deficits in cognitive flexibility or IHTT or abnormalities in neural firing exist in female athletes who have sustained sports-related concussions in the past. Our study offers a unique contribution to the concussion literature because it focuses solely on female athletes and examines potential lasting concussion-related deficits.

This research is important because there are documented gender differences in incidence rates of sports-related concussion as well as the manner by which concussions are sustained (Covassin et al., 2003; McKeever & Schatz, 2003; Gessel et al., 2007), but little research on concussion-related problems in female athletes exists. In addition, while neurological and neurocognitive deficits have been documented in the six month period following a sports-related concussion as well as much later in life, very little research on concussion-related problems in the interim period is available. Thus, to fill these gaps in the concussion literature, we recruited

female athletes whose sports-related concussions occurred at least six months prior to participating and used DFA to determine whether a set of neurocognitive and neurological predictor variables could adequately differentiate these participants from control participants. The six variables used as predictors in the analysis were cognitive flexibility as measured by Stroop switching task completion time, IHTT, and four EEG frequencies: theta, alpha, beta, and gamma. Based on the results of past research, we expected that when results from a Stroop switching task, an interhemispheric transfer task, and data from four EEG frequency bands are used as predictors of concussion status, they should adequately distinguish between control participants and participants who have sustained sports-related concussions in the past.

Although past research suggests that deficits in cognitive flexibility and interhemispheric transfer as well as abnormalities in neural firing are possible in athletes who have sustained sports-related concussions, the DFA did not suggest that this set of predictor variables could significantly differentiate female athletes who had sustained concussions in the past from control participants. Although the result of the DFA was not significant, the predictor variables accounted for a considerable proportion of the variance, and nearly 70% of cases were classified correctly as control or concussion group participants. It is possible that this is because two of the six predictor variables, cognitive flexibility and theta frequency power, were identified as being particularly important contributors. Because these variables were of relative importance, we used follow-up tests which incorporated cases with missing data to further examine these variables.

Previous research on cognitive flexibility and concussion using a Stroop task has shown mixed results (Bruce & Echemendia, 2003; Ellemberg et al., 2007). Bruce and Echemendia (2003) found no significant differences in performance on the color-word version of the Stroop

test between concussed and control athletes while ElleMBERG and colleagues found that the concussed female participants exhibited significant deficits in both cognitive inhibition and flexibility as compared to controls. One important difference between the sample used in the current study and samples used in past research on cognitive flexibility and concussion is that concussion group participants in our study participated nearly three years after their most recent concussion, on average. Bruce and Echemendia (2003) compared athletes two hours to one month post-concussion to controls while ElleMBERG et al. (2007) compared athletes six to eight months post-concussion to controls. It is also important to note that Bruce and Echemendia only studied male athletes.

We expected that deficits in cognitive flexibility would still be apparent in participants who had sustained concussions nearly three years prior to participating, and these deficits would be significant enough to serve as an important predictor variable in the DFA. Although results of the DFA suggest that the six predictor variables together did not significantly differentiate between participants in the control and concussion group, cognitive flexibility was identified one of the most important contributors to group separation. Means for Stroop switching completion time were not in the predicted direction (Table 2); however, follow-up tests on cognitive inhibition and cognitive flexibility suggested that there was no significant difference in Stroop task completion time between control and previously concussed participants (See Table 3 for means).

Additional research is needed to clarify the relationship between sports-related concussions and cognitive flexibility in female athletes in the interim period post-concussion. It is possible that our study did not have sufficient statistical power to detect a difference between control and concussed participants' performance on the Stroop switching task. However,

concussion group participants in our study differed from participants in past research in terms of gender and time since last concussion, so it is possible that female athletes in the interim period after sustaining a concussion differ in terms of cognitive flexibility from participants in past research.

In a review of research on the Stroop task, MacLeod (1991) suggest that although females tend to name colors more quickly than males, there are no significant gender differences on the Stroop task. Nonetheless, because gender differences exist in both incidence rates of concussion and how concussions are sustained (Covassin et al., 2003; McKeever & Schatz, 2003; Gessel et al., 2007), it is possible that gender differences played at least a small role in the mixed results of past research on cognitive flexibility and concussion (Bruce & Echemendia, 2008; ElleMBERG et al., 2007).

Because athletes in our study participated nearly three years on average after their most recent concussion while athletes in the ElleMBERG et al. (2007) study participated six to eight months following a concussion, it is possible that deficits in cognitive flexibility evident in concussed female athletes dissipate over time, and significant differences in cognitive flexibility no longer exist in the interim period. Another potential explanation is that athletes who experience concussions may experience deficits in cognitive flexibility in the recovery period but learn to compensate for these deficits over time, returning performance on cognitive flexibility tasks to baseline or above.

In addition to potential problems with cognitive flexibility, sports-related concussions may cause problems with transfer of information from one hemisphere of the brain to the other. The corpus callosum, the area of the brain important for interhemispheric transfer, has been found to be especially susceptible to concussion-related damage (Hammond-Tooke, et al., 2010;

Nishimoto & Murakami, 1998). Hammond-Tooke et al. (2010) found differences in performance between control and concussed participants on a bimanual reaction time task at one week post-concussion but noted that differences disappeared one month post-injury.

We expected that participants who had sustained concussions over six months prior to participating would continue to show slower interhemispheric transfer rates when a more direct measure of IHT was used, and this would serve as an important predictor in the DFA. Although this hypothesis was not supported, means for IHTT were in the predicted direction (Table 2). It is likely that our study did not have adequate power to detect a difference in IHTT significant enough for it to serve as an important predictor in the DFA. Additional research is necessary to determine whether there is a significant, lasting relationship between sport-related concussions and IHTT.

Reviews on neurological abnormalities associated with concussions suggest that abnormalities in theta, alpha, beta, and gamma frequencies are fairly common in athletes who have sustained sports-related concussions (Thatcher, 2006; Thompson & Hagedorn, 2012). However, to date, post-concussion EEG studies have been done primarily on male athletes (e.g. landmark studies by Thatcher et al., 1989 and McCrea et al., 2007). In addition, post-concussion EEG recording for these studies took place during the recovery period (i.e. between one and forty-five days after a concussion was sustained) rather than the interim period, which is the focus of the current study.

Previous research suggests that athletes who have sustained concussions show increased theta activity, which is generally associated with increased cognitive processing and awareness (Hughes & John, 1999; Ray & Slobounov, 2006; Tatum, 2008; Thompson & Hagedorn, 2012). Previous research also suggests that sports-related concussions are associated with decreased

alpha, beta, and gamma (Hughes & John, 1999; Thatcher, 2006; Thompson & Hagedorn, 2012). Alpha activity is associated with overall relaxation and active cognition, beta activity is associated with overall alertness and cognitive activation, and gamma activity is associated with integration of parts into a whole (Ray & Slobounov, 2006).

Although most concussion research that utilizes EEG technology has been done within ten days of injury, recent ERP research suggests that neurological abnormalities which contribute to more effortful processing may exist even thirty years post-concussion (DeBeaumont et al., 2009). Thus, we expected to observe electrophysiological abnormalities in athletes who had sustained concussions nearly three years prior to participating in our study.

Based on results of past EEG research, we expected to observe abnormalities in power of four EEG frequency bands in particular. We hypothesized that EEG readings would show increased theta power and decreased alpha, beta, and gamma power in participants who had sustained concussions in the past, and we predicted that these four EEG measurements would be important predictor variables in the DFA. This pattern of expected abnormalities would replicate EEG patterns found in the concussion literature.

Although theta frequency power was identified in the DFA as an important contributor to group separation, means were not in the originally predicted direction (Table 2). A follow-up test on theta demonstrated that control participants had significantly more theta activity than participants in the concussion group (Table 3). Participants who have sustained concussions in the past may display less overall active cognition and awareness than control participants even after the initial recovery period.

This trend is opposite of the trend found in previous literature in regards to theta activity (Hughes & John, 1999; Thompson & Hagedorn, 2012). However, it is possible that differences

in the sample and timing of this study may be implicated in this trend reversal. Because past research on concussion-related EEG abnormalities utilized primarily male participants while our study focuses exclusively on female athletes and gender differences in neural firing exist (Wada, Takizawa, Zheng-Yan, & Yamaguchi, 1994), it is possible that gender differences in neural firing play a role in the theta power trend reversal found in our study. Another possible explanation for the opposite trend in theta power found in our study is that our study focuses on concussion-related EEG abnormalities after the initial recovery period, while past research has measured EEG frequency power in the days following a concussion. It is possible that there is an initial spike in theta power following an injury followed by decreased theta activity after the initial recovery period. Concussion-related damage to acetylcholine neurons, the major producers of theta waves, may cause over-excitation of the neurons, leading to increased theta power following a concussion. However, over time the damage may lead to cell death and decreased theta activity. Because theta activity is also generally associated with working memory and memory consolidation, as well as hippocampal activity, this may therefore be one link between concussions and increased later life memory deficits demonstrated by athletes who suffer from mTBI (Klimesch, 1999; Kahana, 2006).

When control and concussion group theta data was analyzed together, there was significantly more theta activity in the right hemisphere than the left. Although it is not uncommon to find hemispheric differences in power for some EEG frequency bands, there is little evidence of asymmetry for the theta frequency band in normal populations (Tatum, 2008). It is possible that this difference is related to underlying differences in information processing in a population of athletes. The right hemisphere is particularly important in spatial processing

(Brown & Jaffe, 1975; Shulman et al., 2010), and it could be more active overall in athletes than non-athletes due to their increased use of spatial skills.

Overall, although results of the DFA were not significant, a sizeable proportion of the variance was accounted for by the predictor variables, and cognitive flexibility and theta power were particularly important in differentiating between participants in the control and concussion groups. Follow-up tests on Stroop switching task performance and theta power which included participants who were not used in the DFA (due to missing data), aimed to further clarify the role of cognitive flexibility and theta power. Although Stroop switching performance was not significantly different for control and concussion group participants, participants who had sustained one or more sports-related concussions in the past showed significantly less overall theta activity than controls.

### **Limitations**

Past research suggests neurocognitive and neurological issues exist in the days, weeks, and months after an athlete sustains a concussion, and concussion-related problems are sometimes evident much later in life in the form of a MCI, CTE, and other types of dementia. Although a sizable proportion of cases were classified as control participants or concussion participants in this study, the six predictor variables did not significantly discriminate between participants who had never sustained a concussion and participants who had sustained sports-related concussions in the past.

This is likely because the study did not have sufficient power to detect a rather small effect: concussion-related deficits or abnormalities in the interim period. One explanation for this reduced statistical power is the small sample size. Recruiting participants who met the particularly rigorous exclusion criteria proved to be especially difficult. In addition to

identifying as female athletes who had not sustained a concussion in the past six months, participants had to be right-handed and report no diagnoses of neurological or attentional disorders. Although we offered monetary compensation or course research credit for participation, only forty-six participants were recruited.

The chosen statistical analysis also limited sample size. DFA requires all data points for each participant in the analysis, so several participants who had missing data due to equipment malfunctions were not included in the original data analysis. Due to the small number of participants included in the DFA, our study likely did not have adequate power to use the six predictor variables to classify a statistically significant proportion of cases.

Another limitation of our study involved the revision of the IHT task during data collection. Although data from the original and revised versions of the task were treated as one variable in the DFA, the fact that some of the participants completed an easier IHT task represents a confounding variable in the study.

### **Future Directions**

Further research is needed to determine whether deficits related to the predictor variables used in this study are observable in female athletes beyond the initial recovery period for concussion. Although this study likely did not have adequate power to use the predictors to differentiate between control and concussed participants using DFA, follow-up testing on theta power suggests that participants who have sustained concussions in the past show significantly less overall theta power. Because the current study differed from previous research in terms of gender of the participants and timing of most recent concussion, future research is necessary to replicate this effect and clarify the basis of the trend displayed in this study.

Because past research suggests neurocognitive and neurological concussion-related deficits may manifest as MCI, CTE, or other types of dementia later in life, it is important to continue examination and treatment of concussion-related issues after the initial six month recovery period, particularly when an athlete has had multiple concussions. Additional research is needed to clarify the potential effects of sports-related concussions in female athletes.

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## Appendix

## Figures and Tables

<b>Study Title</b> Cognitive Flexibility, Interhemispheric Transfer, and QEEG in Concussed Female Athletes	
<b>Study Purpose and Rationale</b> This experiment examines the effect of concussions on female athletes in order to examine if past concussions have an effect on athletes' neural firing patterns, rates of interhemispheric transfer, and cognitive flexibility.	
<b>Inclusion/Exclusion Criteria</b> To be eligible to participate in this study, you must have participated in an organized, intramural, or club sport within the past year. You must <i>not</i> have sustained a concussion (diagnosed by a medical professional) in the past six months. You must be right-handed, <i>not</i> taking psychopharmaceutical medications (e.g. antidepressants, anti-anxiety medication, anti-psychotics, etc.), and <i>not</i> diagnosed with, mental health, attentional, or neurological, disorders.	
<b>Participation Procedures and Duration</b> For this project, you will be asked to complete surveys regarding your handedness and neurological health history. You will then undergo five minutes of EEG recording and complete a computerized interhemispheric transfer task and a test of cognitive flexibility. The entire experiment should take approximately an hour to complete including consent and survey completion.	
<b>Data Confidentiality or Anonymity</b> All data will be maintained as confidential and no identifying information such as names will appear in any publication or presentation of the data.	
<b>Storage of Data</b> Data will remain confidential. All data collected on the computer will remain accessible only by IRB-approved members of the lab and encoded by an anonymous numerical ID that will not be linked to the participant's identity. Survey data and cognitive flexibility test data will be stored for three years in a locked file in the lab and also encoded by a numerical ID not linked to the participant's identity.	
<b>Risks or Discomforts</b> There are no anticipated risks to this study. If at any time during the course of the experiment you feel uncomfortable or wish to stop, you may do so at any time.	
<b>Benefits</b> The results of this study will help to develop our understanding of the effects of concussions on cognitive flexibility, interhemispheric transfer, and neural firing patterns.	
<b>Voluntary Participation</b> Your participation in this study is completely voluntary and you are free to withdraw your permission at anytime for any reason without penalty or prejudice from the investigator. Your decision to participate or not will not impact your athletic status in any way (team or club). Please feel free to ask any questions of the investigator before signing this form and at any time during the study.	
<b>IRB Contact Information</b> For questions about your rights as a research subject, please contact the Director, Office of Research Compliance, Ball State University, Muncie, IN 47306, (765) 285-5070 or at <a href="mailto:irb@bsu.edu">irb@bsu.edu</a> .	
<b>Study Title</b> Cognitive Flexibility, Interhemispheric Transfer, and QEEG in Concussed Female Athletes	
<b>Consent</b>  I, _____, agree to participate in this research project entitled, "Cognitive Flexibility, Interhemispheric Transfer, and QEEG in Concussed Female Athletes." I have had the study explained to me and my questions have been answered to my satisfaction. I have read the description of this project and give my consent to participate. I understand that I will receive a copy of this informed consent form to keep for future reference.  To the best of my knowledge, I meet the inclusion/exclusion criteria for participation (described on the previous page) in this study.  _____ Participant's Signature  _____ Date	
<b>Researcher Contact Information</b> Principal Investigator:  Kelly Fogle Dept. of Psychological Science Ball State University Muncie, IN 47306 Telephone: 260-750-9954 Email: <a href="mailto:klfogle@bsugmail.net">klfogle@bsugmail.net</a>  Dr. Simon-Dack Dept. of Psychological Science Ball State University Muncie, IN 47306 Telephone: (765)285-1693 Email: <a href="mailto:slsimondack@bsu.edu">slsimondack@bsu.edu</a>	

Figure 1. Informed consent for PSYS 100 participants.

**Study Title** Cognitive Flexibility, Interhemispheric Transfer, and QEEG in Concussed Female Athletes

**Study Purpose and Rationale**

This experiment examines the effect of concussions on female athletes in order to examine if past concussions have an effect on athletes' neural firing patterns, rates of interhemispheric transfer, and cognitive flexibility.

**Inclusion/Exclusion Criteria**

To be eligible to participate in this study, you must have participated in an organized, intramural, or club sport within the past year. You must *not* have sustained a concussion (diagnosed by a medical professional) in the past six months. You must be right-handed, *not* taking psychopharmaceutical medications (e.g. antidepressants, anti-anxiety medication, anti-psychotics, etc.), and *not* diagnosed with, mental health, attentional, or neurological disorders.

**Participation Procedures and Duration**

For this project, you will be asked to complete several surveys regarding your handedness and neurological health history. You will then undergo five minutes of EEG recording and complete a computerized interhemispheric transfer task and a test of cognitive flexibility. The entire experiment should take approximately an hour to complete including consent and survey completion. You will receive payment (\$10/hour or \$10 for any portion of an hour) prior to leaving.

**Data Confidentiality or Anonymity**

All data will be maintained as confidential and no identifying information such as names will appear in any publication or presentation of the data.

**Storage of Data**

Data will remain confidential. All data collected on the computer will remain accessible only by IRB-approved members of the lab and encoded by an anonymous numerical ID that will not be linked to the participant's identity. Survey data and cognitive flexibility test data will be stored for three years in a locked file in the lab and also encoded by a numerical ID not linked to the participant's identity. Payment information (a list of names of who received payment) will be completely unassociated with the subject IDs.

**Risks or Discomforts**

There are no anticipated risks to this study. If at any time during the course of the experiment you feel uncomfortable or wish to stop, you may do so at any time.

**Benefits**

The results of this study will help to develop our understanding of the effects of concussions on cognitive flexibility, interhemispheric transfer, and neural firing patterns.

**Voluntary Participation**

Your participation in this study is completely voluntary and you are free to withdraw your permission at anytime for any reason without penalty or prejudice from the investigator. Your decision to participate or not will not impact your athletic status in any way (team or club). Please feel free to ask any questions of the investigator before signing this form and at any time during the study.

**IRB Contact Information**

For questions about your rights as a research subject, please contact the Director, Office of Research Compliance, Ball State University, Muncie, IN 47306, (765) 285-5070 or at [irb@bsu.edu](mailto:irb@bsu.edu).

**Study Title** Cognitive Flexibility, Interhemispheric Transfer, and QEEG in Concussed Female Athletes

**Consent**

I, \_\_\_\_\_, agree to participate in this research project entitled, "Cognitive Flexibility, Interhemispheric Transfer, and QEEG in Concussed Female Athletes." I have had the study explained to me and my questions have been answered to my satisfaction. I have read the description of this project and give my consent to participate. I understand that I will receive a copy of this informed consent form to keep for future reference.

To the best of my knowledge, I meet the inclusion/exclusion criteria for participation (described on the previous page) in this study.

\_\_\_\_\_  
Participant's Signature

\_\_\_\_\_  
Date

**Researcher Contact Information**

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Figure 2. Informed consent for paid participants.

**Health Survey**

Participant Code: \_\_\_\_\_

The following set of questions is to screen for factors known to affect information processing. Please be as honest as possible, and complete all questions to the best of your ability.

1. What is your date of birth?
2. What sport(s) (organized, intramural, or club) do you participate in?
3. Have you ever sustained a sports-related concussion? YES NO  
If yes, please list the date sustained, person who diagnosed the concussion, and a brief explanation of how it was sustained.

Date:	Diagnosed by:	How was the concussion sustained?

4. Since birth have you ever had any other medical problems? YES NO  
If yes, please explain.
5. Since birth have you ever been hospitalized? YES NO  
If yes, please explain.
6. Are you currently taking any medications? YES NO  
If yes, please list them all including birth control.
7. Do you have now or have you ever had any of the following? Check yes or no.

Neurological disorder	<input type="checkbox"/>	YES	<input type="checkbox"/>	NO
Brain disorder	<input type="checkbox"/>	YES	<input type="checkbox"/>	NO
Vascular disorder	<input type="checkbox"/>	YES	<input type="checkbox"/>	NO
Stroke	<input type="checkbox"/>	YES	<input type="checkbox"/>	NO
Attention-deficit disorder	<input type="checkbox"/>	YES	<input type="checkbox"/>	NO
Hyperactivity	<input type="checkbox"/>	YES	<input type="checkbox"/>	NO

If you checked yes for any of the items in question 7, please describe your diagnosis briefly.

Figure 3. Health survey.

**Edinburgh Handedness Inventory**

Please indicate your preferences in the use of hands in the following activities by putting a check in the appropriate column. Where the preference is so strong that you would never try to use the other hand, unless absolutely forced to, put 2 checks. If in any case you are really indifferent put and a check in both columns.

Some of the activities listed below require the use of both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try and answer all of the questions, and only leave a blank if you have no experience at all with the object or task.

	Left	Right
1. Writing	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
2. Drawing	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
3. Throwing	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
4. Scissors	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
5. Toothbrush	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
6. Knife (without fork)	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
7. Spoon	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
8. Broom (upper hand)	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
9. Striking Match (match)	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
10. Opening box (lid)	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
<b>TOTAL (count X's in both columns)</b>		

**Scoring:**  
 Add up the checks in both left and right columns.  
 Whichever number is greater, would be considered your handedness.

Figure 4. Edinburgh Handedness Inventory.

	Stimulus:	Correct Response:	Stimulus:	Correct Response:	Stimulus:	Correct Response:	Stimulus:	Correct Response:
Subtask 1:		Red		Blue		Green		Yellow
Subtask 2:	<b>RED</b>	Red	<b>BLUE</b>	Blue	<b>GREEN</b>	Green	<b>YELLOW</b>	Yellow
Subtask 3:	<b>BLUE</b>	Red	<b>GREEN</b>	Blue	<b>YELLOW</b>	Green	<b>RED</b>	Yellow
Subtask 4:	<b>GREEN</b>	Red	<b>BLUE</b>	Blue	<b>RED</b>	Green	<b>YELLOW</b>	Yellow

Figure 5. Example of the Stroop subtasks.

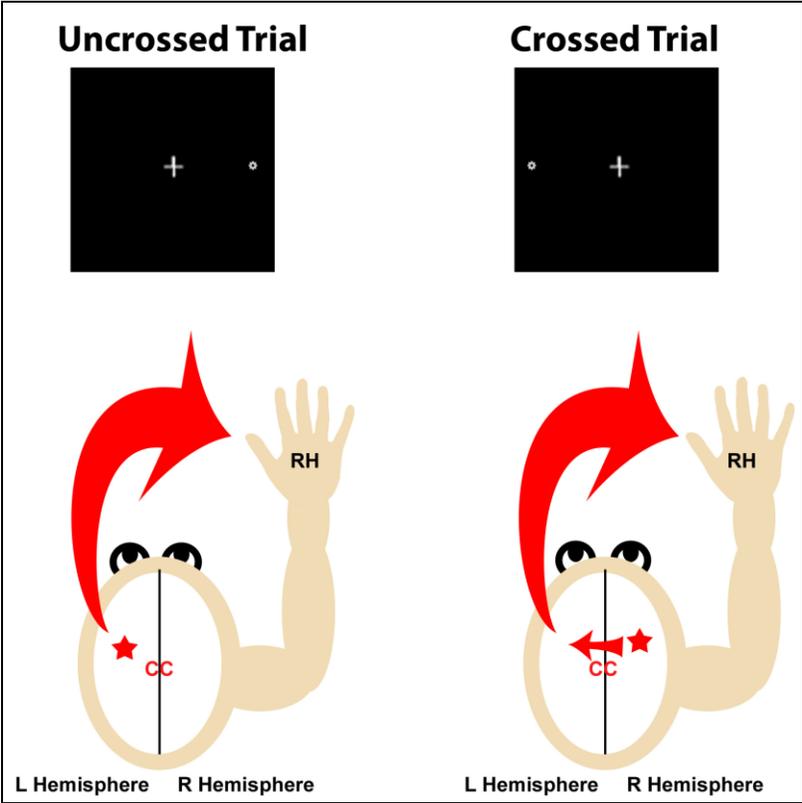


Figure 6. Theoretical basis for the IHT task

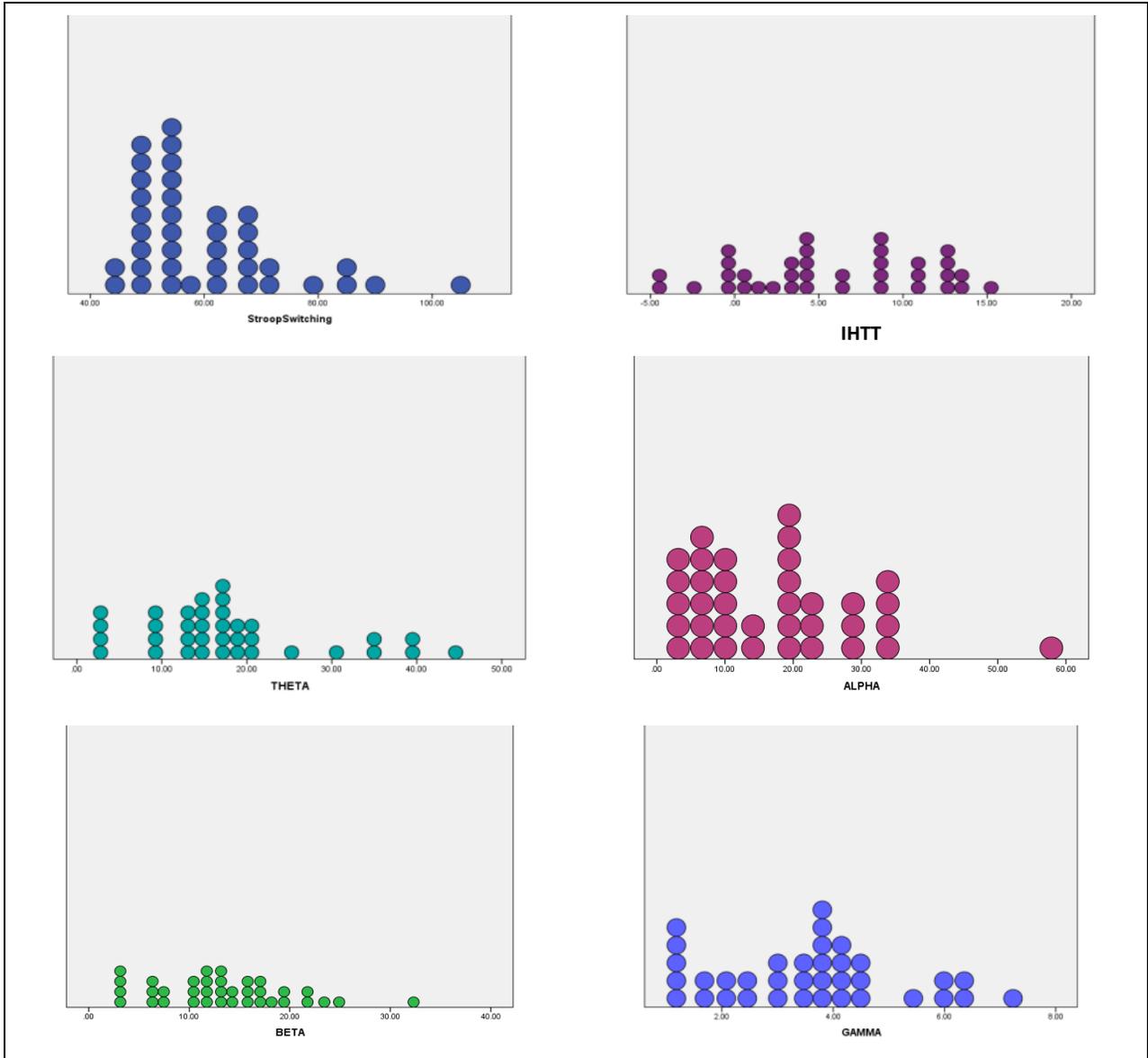


Figure 7. Evidence for predictor variable normality and absence of outliers

Note. DFA assumes that predictor variable data follows a normal distribution and there are no outliers.

<sup>a</sup> Scales for Stroop and IHTT are in seconds, and scales for EEG frequencies are in  $mV^2$ .

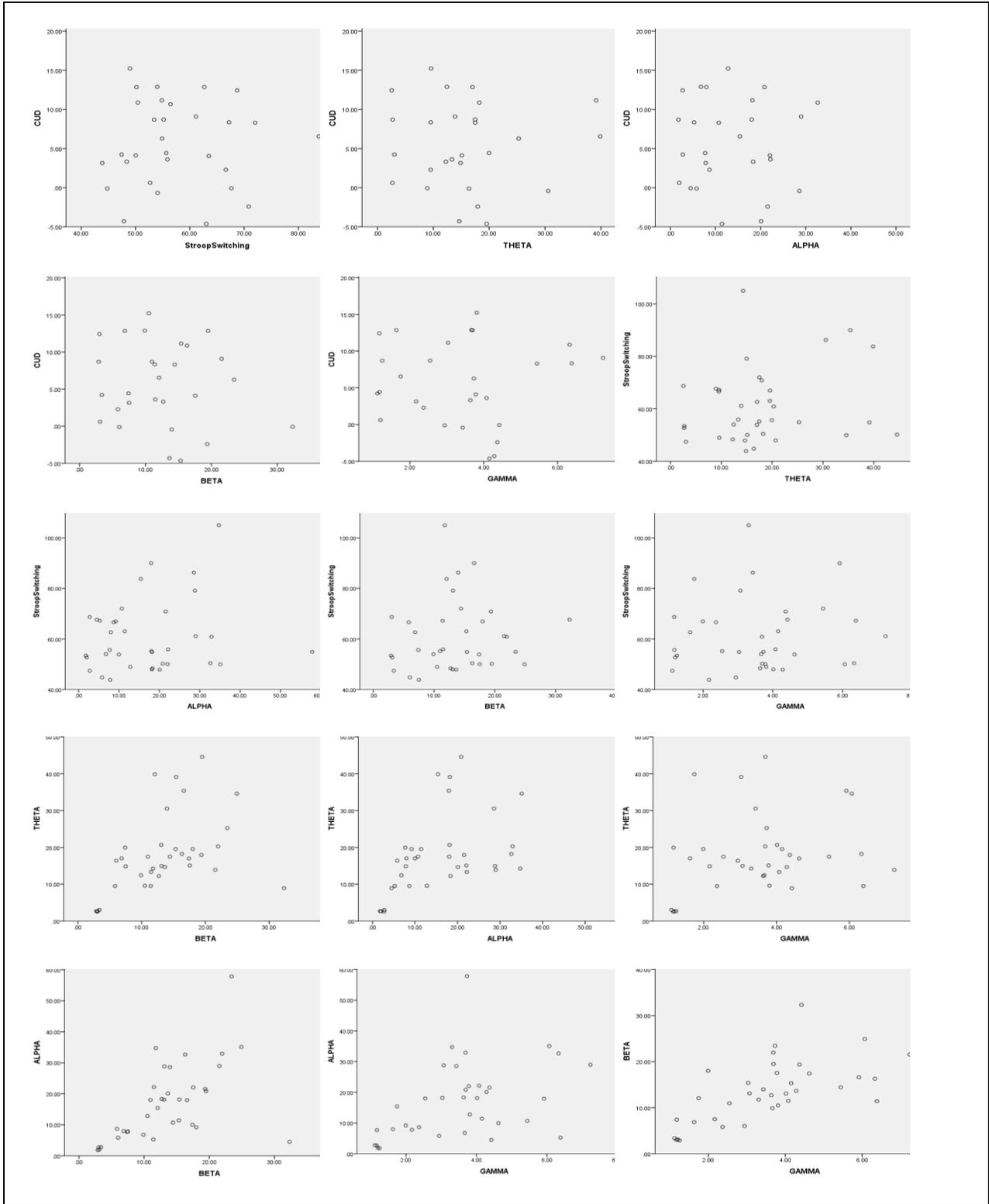


Figure 8. Linearity of pairs of predictor variables.

Note. DFA assumes relationships between predictor variables are linear.

Table 1

*Evidence of Multicollinearity and Singularity*

	<u>Stroop</u> <u>Switching</u>	<u>IHTT</u>	<u>Theta</u>	<u>Alpha</u>	<u>Beta</u>	<u>Gamma</u>
Stroop Switching	1	-0.10	-0.25	0.03	0.19	0.09
IHTT		1	0.11	0.003	-0.13	0.01
Theta			1	0.47*	0.40*	0.10
Alpha				1	0.58**	0.44*
Beta					1	0.65**
Gamma						1

*Note.* High correlations between predictor variables are suggestive of multicollinearity, an assumption violation for DFA.

\* $p < 0.05$ . \*\* $p < 0.01$ .

Table 2

*Means for DFA Predictor Variables*

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	<u>Control Group (n=14)</u>	<u>Concussion Group (n=14)</u>
Stroop Switching	62.57	54.46
IHTT	4.86	6.42
Theta	20.25	13.22
Alpha	14.79	15.46
Beta	12.43	12.41
Gamma	3.21	3.56

Table 3

*Means for Variables in Follow-up Tests*

	<u>Control Group</u>	<u>Concussion Group</u>
Stroop Switching	63.00 (n=21)	57.96 (n=18)
Stroop Inhibition	7.86 (n=21)	8.58 (n=18)
Theta	21.42 (L = 20.20, R = 21.33) (n=18)	14.44 (L = 13.80, R = 14.16) (n=18)

*Note.* Ns for follow-up tests differed from Ns for DFA because cases with missing data were included in the follow-up test.