



## Changes in brain connectivity following exposure to bilateral eye movements

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### ABSTRACT

The present research assessed how engaging in bilateral eye movements influences brain activity. Participants had their resting-state brain activity recorded with electroencephalography (EEG) before and after they performed 30 s of bilateral eye movements or a center-control manipulation. We assessed differences in change scores for absolute power and coherence between the eye-movement and center-control conditions. A main effect for handedness was present for EEG power in the theta and beta frequency bands, with inconsistent-handed participants displaying a greater increase than consistent-handed participants in both frequency bands. For theta, the increase in power for inconsistent handlers was specific to participants in the bilateral eye-movement condition, whose increase in theta power exceeded the increase in theta power for consistent-handed participants regardless of condition. In contrast, for coherence, a main effect for condition was present for the delta frequency band, with participants in the control condition exhibiting a significant drop in posterior delta coherence pre to post. We suggest that the maintenance of posterior delta coherence over time may be an important factor in sustaining attention. Further, the malleability of EEG power for inconsistent-handed participants reveals the importance of individual-differences variables in the potential for behavioral manipulations to change brain activity.

### 1. Introduction

Performing bilateral eye movements, moving the eyes horizontally from left to right, has been associated with beneficial clinical and cognitive effects; however, the neural underpinnings of the eye movements' effects remain unclear. Positive results following bilateral eye movements include improved outcomes in patients with Post-traumatic Stress Disorder (PTSD; Shapiro, 2014), as well as cognitive enhancements in memory, attention, and creativity (e.g., Christman, Garvey, Propper, & Phaneuf, 2003; Edlin & Lyle, 2013; Shobe, Ross, & Fleck, 2009). Existing theories propose that bilateral eye-movements change communication between the hemispheres (Christman et al., 2003) or engage executive attention (Lyle & Martin, 2010); yet, other possibilities exist, such as global changes in cortical arousal (Stenberg, 1992). Neuroimaging methods can inform existing theories surrounding the eye movements' impact, but to date few researchers have assessed the influence of repetitive bilateral eye movements on brain activity (c.f., Propper, Pierce, Geisler, Chirstman, & Bellorado, 2007; Samara, Elzinga, Slagter, & Nieuwenhuis, 2011). Understanding the neural changes that occur in response to bilateral eye movements may provide

clinicians and researchers with a consistent and effective manipulation that can be implemented to induce change.

Researchers have used bilateral eye movements to enhance clinical and cognitive outcomes for decades. Shapiro (1989) initially introduced bilateral eye movements in clinical settings as a component of Eye-Movement Desensitization and Reprocessing (EMDR) therapy for the treatment of PTSD. Shapiro proposed that bilateral eye movements were effective in mitigating or eliminating trauma symptoms by altering the structure of the initial traumatic memory by incorporating non-stressful content into the source memory. Empirical studies of EMDR have specifically associated the eye-movement component of the treatment with a decrease in the vividness and emotional content of trauma-related memories (Leer, Engelhard, & van den Hout, 2014). Moreover, neuroimaging research exploring the neural changes following EMDR has revealed that patients with trauma symptomology experienced a decrease in limbic system activation, coupled with an increase in activation over temporal and occipital regions upon completion of EMDR (Pagani et al., 2012).

Although random clinical trials have supported the efficacy of EMDR in the reduction of stress symptoms (e.g., Lee & Drummond,

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2008; Lilley, Andrade, Turpin, Sabin-Farrell, & Holmes, 2009; Shapiro, 2014), there remains significant debate in the field as to the role that the eye movements actually play in the treatment's effectiveness (see Pagani & Carletto, 2017). Some researchers have reported that EMDR is no more effective in reducing PTSD symptoms than other therapies that focus on reducing trauma (e.g., exposure therapy; Seidler & Wagner, 2006; Taylor, Thordarson, Maxfield, Fedoroff, & Paul's Hospital, S., Lovell, K., & Ogradniczuk, J., 2003). However, a recent meta-analysis revealed that EMDR produced slightly larger effect sizes in treatment outcomes than other trauma-focused therapies, suggesting that the eye movements contribute something unique to treatment results (Lee & Cuijpers, 2013). Although the efficacy of EMDR may be unknown, our exploration of the neural correlates of bilateral eye movements in cognition is important in its own right and is of value independent of any clinical relevance our results may have to EMDR.

As an extension to the initial clinical inquiries, researchers explored potential cognitive benefits associated with bilateral eye movements (Christman & Garvey, 2001; Christman et al., 2003; Christman, Propper, & Dion, 2004). During the bilateral eye-movement manipulation, participants track a dot that alternates in location between the left and right sides of the computer screen every 500 ms, with the dot locations separated by 27° of visual angle. Christman et al. (2003) initially proposed the Interhemispheric Interaction (IHI) Theory to explain how bilateral eye-movements affect cognition and mood. The IHI theory suggests that moving the eyes laterally, from left to right, increases activation in both hemispheres, thereby increasing interhemispheric communication. Increasing interhemispheric communication purportedly enhances mood and cognition. Researchers initially explored the eye movements' effects on episodic memory, due to hemispheric differences in the brain's contributions to episodic memory and retrieval (see the *Hemispheric Encoding/Retrieval Asymmetry (HERA) Model*; Tulving, Kapur, Craik, Moscovitch, & Houle, 1994). Over time, researchers have observed cognitive benefits following bilateral eye movements in a several domains, such as memory, attention, and creativity (e.g., Christman et al., 2004; Lyle & Edlin, 2014; Shobe et al., 2009).

Although cognitive researchers have observed enhancements stemming from bilateral eye movements, neuroimaging research testing the IHI theory has produced mixed results (e.g., Propper et al., 2007; Samara et al., 2011). Propper et al. (2007) used electroencephalography (EEG) to measure the change in electrical activity between the hemispheres after participants completed 30 s of bilateral eye movements. Contrary to the prediction of increased interhemispheric interaction, proposed by the IHI theory (Christman et al., 2003), Propper et al. observed reduced coherence in the gamma frequency band (35–54 Hz) between frontal electrode sites Fp1 and Fp2 after exposure to the bilateral eye-movement manipulation, when compared to a center-control manipulation. In a more comprehensive analysis of post-eye-movement changes, Samara et al. (2011) explored the behavioral and neural effects of bilateral eye movements, using additional homologous electrode sites and six frequency bands. The researchers observed enhanced memory for emotion words in participants who completed the bilateral eye movements. However, the only significant change in EEG coherence following the eye-movement manipulation was found for the alpha frequency band between electrodes FT7 and FT8. Similar to the findings reported in Propper et al., the eye-movement condition experienced a decrease in alpha coherence pre to post.

Most recently, Keller, Stevens, Lui, Murray, and Yaggie (2014) examined changes in resting-state EEG in participants who performed bilateral eye movements while retrieving a positive emotional memory from childhood. Although the researchers failed to observe an increase in interhemispheric coherence, they did observe an increase in intrahemispheric coherence over the frontal regions for delta and beta coherence. Related work by Yaggie et al. (2015) reported increases in intrahemispheric coherence in theta and beta frequency bands for participants who performed bilateral eye movements while retrieving

negative emotional memories. In addition, Keller et al. reported an increase in the vividness of positive memories across trials, whereas Yaggie et al. observed a decrease in vividness for negative memories across successive trials. Keller et al. indicated that the coherence changes observed during the post eye movement interval may have stemmed from the memory retrieval task performed concurrently with the eye movement manipulation, and not the eye movements themselves. Further, Keller et al. speculate that different electrophysiological changes may occur in response to the eye movements if the eye movements are performed in conjunction with tasks supported by other cognitive processes (e.g., creative thought). Hence, while few changes in coherence have been detected between the hemispheres following the eye-movement manipulation across studies, these changes have all been in the form of reduced coherence.

The absence of neuroimaging findings in support of the IHI theory, coupled with behavioral results that failed to support IHI, led researchers to consider other possibilities regarding the eye-movements' impact on cognition. Lyle and Martin (2010) proposed an attentional control (AC) hypothesis, which suggests that engaging in bilateral eye movements activates the frontoparietal attention network and, as a result, enhances subsequent performance on tasks that require attentional control. The AC hypothesis contends that performing bilateral eye-movements is a low-level executive control task and that the use of executive control to complete this manipulation prepares the individual to engage in subsequent processes that require a high degree of top-down executive control (e.g., goal-driven selective attention; Edlin & Lyle, 2013). Research exploring the impact of bilateral eye movements on executive, orienting, and alerting attention networks revealed post eye-movement facilitation exclusively within the executive attention network (Edlin & Lyle, 2013). Moreover, Edlin and Lyle (2013) assert that the tasks examined to date that have been associated with improvements following bilateral eye movements (e.g., episodic memory, attention, and creativity) all involve significant executive control processes.

Although we know of no direct neural exploration of the AC theory (Lyle & Martin, 2010; see also Edlin & Lyle, 2013) to date, changes in activation in conjunction with lateral eye movements have been reported in the brain's attention pathways, such as the frontoparietal attention network. Context-dependent eye movements in nonhuman primates generate post-saccadic activity in the prefrontal cortex (see Funahashi, 2014, for a review). This post-saccadic activity is different from the activation that occurs in the frontal eye fields regardless of whether the eye movements are goal directed or spontaneous in nature. Funahashi (2014) suggests that residual brain activity following goal-directed saccades may contribute positively to the cognitive processing performed by the prefrontal cortex, such as during memory termination or response monitoring. Further, research has revealed that activity in the intraparietal cortex, along with the frontal eye fields, can be detected during planning and then executing goal-directed behavior (see Corbetta & Shulman, 2002, for a review). As a final source of support for a link between eye movements and executive attention, activation in regions of the frontoparietal attention network occurs when individuals perform memory retrieval and attention tasks (Naghavi & Nyberg, 2005; Vincent, Kahn, Snyder, Raichle, & Buckner, 2008; Wagner, Shannon, Kahn, & Buckner, 2005), and when coordinating eye movements (Corbetta & Shulman, 2002). Thus, it is feasible that bilateral eye movements influence cognition and mood through their influence on the frontoparietal attention network, an integral network in task-directed cognition (see Mantini, Perrucci, Del Gratta, Romani, & Corbetta, 2007).

The present research explored the neural changes in resting-state EEG that occur in response to bilateral eye movements. We recorded participants' resting-state brain activity before and after a 30 s eye-movement manipulation, or a center-control condition, as administered in prior research (e.g., Christman et al., 2003; Shobe et al., 2009). We tested the changes in EEG power and coherence following the eye-

movement manipulation for evidence in support of the IHI and AC theories, but remained open to the possibility that the eye-movements influence cognition via another mechanism. EEG coherence is a measure of the synchronous activity among brain regions and is indicative of underlying network connectivity (Thatcher, 2012).

Prior research has revealed differences in the eye movements' effects on cognition for individuals who are consistent- versus inconsistent-handed, with consistent handers garnering greater benefits (e.g., Lyle, Logan, & Roediger, 2008; Parker & Dagnall, 2010). In general, task performance without exposure to the eye-movement manipulation is superior for inconsistent handers when compared to consistent handers in episodic memory retrieval (Lyle et al., 2008; Propper, Christman, & Phaneuf, 2005) and cognitive flexibility (Christman, Henning, Geers, Propper, & Niebauer, 2008; Shobe et al., 2009; see Prichard, Propper, & Christman, 2013, for a review). However, exposure to bilateral eye movements prior to cognitive tasks enhances performance for consistent handers on episodic memory and creativity tasks (e.g., Christman et al., 2003; Shobe et al., 2009). Inconsistent handers, on the other hand, have been shown to garner no benefit from the eye movement manipulation (e.g., Christman et al., 2003; Shobe et al., 2009) or, in some cases, show a drop in performance from baseline (Lyle et al., 2008; Lyle, Hanaver-Torrez, Hackländer, & Edlin, 2012). Despite differences in the eye-movement manipulation's efficacy in consistent versus inconsistent handers, neuroimaging studies exploring bilateral eye movements to date have not studied handedness as a variable in their designs. Prior work by Propper and Christman (2008) and Keller et al. (2014) recorded data from right-handed participants with no indication of participants' handedness scores, whereas Samara et al. (2011) and Yaggie et al. (2015) tested participants who were dominantly right handed. Due to the variability of behavioral results observed when inconsistent handers are exposed to bilateral eye movements, we incorporated handedness as an independent variable in our design.

## 2. Method

### 2.1. Participants

Undergraduate students ( $N = 91$ ) from Stockton University participated in exchange for extra or required credit in a psychology course. Participants enrolled in the study through an online psychology research website (SONA). Participants were between the ages of 18 and 45 years with normal or corrected to normal vision, who indicated no history of neurological disorder or traumatic brain injury, or a history of drug and alcohol abuse. Descriptive statistics for age, gender, and

handedness for the participants included in the final sample are presented by condition in Table 1.

### 2.2. Materials

#### 2.2.1. EEG

EEG data were recorded using a 129-channel HydroCel Geodesic Sensor Net, with Cz reference (Electrical Geodesics, Inc.). Sensor impedance levels were below 50 K $\Omega$ , appropriate for use with the Net Amps 300 high-impedance amplifier. Data were sampled at 250 Hz, and filtered using an analog 0.1–100 Hz band-pass filter. All data were recorded using Net Station 4.3 software. Recordings included four minutes of resting-state data before the visual manipulation (pre) and four minutes of resting-state data after the manipulation (post).

EEG data were processed offline using EEGLAB 12 (Delorme & Makeig, 2004), supplemented by MATLAB scripts, run using Matlab 2013a (Mathworks, Natick, MA, USA). Channels with no data were removed from the EEG files before the data were filtered in EEGLAB using a band-pass filter (0.2–50 Hz) and then segmented into 2-s epochs. Files were visually inspected to remove epochs containing gross artifact. Files were then subject to independent component analysis and the resulting components were processed for eye-blink and eye-movement artifact using ADJUST 1.1 (Mognon, Jovicich, Bruzzone, & Buiatti, 2011), a plug-in available for use on the EEGLAB platform. Components identified as artifact were removed from the data and the files were visually inspected a second time to ensure no artifact remained.

After final visual review, missing or bad channels were interpolated from neighboring channels and the data were re-referenced to average reference before undergoing baseline correction. The mean number of interpolated channels was 9.97 ( $SD = 4.28$ ); there were no differences in channel interpolation between condition or handedness groups ( $p > 0.05$ ). The mean number of artifact-free epochs that remained for analysis was 166.79 ( $SD = 23.98$ ). Participant files with less than 60% of the initial epochs (i.e., less than 4.8 min) remaining for analysis following data cleaning were not included in the analyses ( $n = 5$ ), leaving 86 files for analysis. Power spectral density for the remaining epochs was estimated using MATLAB's Fast Fourier Transformation function. Power spectra were estimated for each epoch separately, and spectra from epochs within the same block were averaged before mean power estimates were calculated for the 19 electrodes in the Standard 10–20 System for the following frequency bands: delta (1.0–4.0 Hz), theta (4.0–8.0 Hz), alpha (8.0–13.0 Hz), beta (13.0–30.0 Hz), and gamma (30.0–45.0 Hz).

Coherence was calculated separately for each of the 171 electrode combinations using the following formula:

**Table 1**  
Descriptive statistics by condition.

	Eye-movement		Control	
	Consistent	Inconsistent	Consistent	Inconsistent
Sample size	30	13	31	12
Female	26	12	28	8
Male	4	1	3	4
Age	19.50 (1.70)	19.38 (2.10)	20.16 (3.30)	19.58 (1.56)
Handedness	92.83 (7.95)	56.54 (14.05)	93.06 (7.03)	64.17 (8.48)
PANAS – Positive	33.80 (5.72)	32.23 (5.54)	33.22 (4.81)	34.65 (5.24)
PANAS – Negative**	20.23 (6.90)	22.15 (5.65)	19.06 (5.02)	16.67 (4.27)
PANAS – SF – Positive	14.40 (4.57)	10.69 (3.92)	13.29 (4.97)	12.94 (3.89)
PANAS – SF – Negative	5.62 (1.44)	5.62 (1.12)	6.16 (1.66)	5.50 (1.45)
Extroversion	4.48 (1.59)	4.81 (1.27)	4.44 (1.44)	4.50 (1.52)
Agreeableness	5.03 (1.01)	4.85 (0.90)	4.94 (0.89)	4.75 (0.99)
Conscientiousness**	6.06 (0.87)	5.62 (0.94)	5.69 (0.96)	6.12 (0.75)
Emotional Stability	4.63 (1.09)	4.69 (1.49)	4.65 (1.40)	5.33 (1.15)
Openness to Experience	5.35 (1.23)	5.81 (0.88)	5.53 (1.16)	5.33 (1.23)

\*\* Differences were observed among conditions in pre-manipulation assessments for these variables. PANAS-SF variables were administered after the visual manipulation.

$$\text{Coh}_{ij}(f) = |C_{ij}(f)| = \left| \frac{S_{ij}(f)}{(S_{ii}(f)S_{jj}(f))^{1/2}} \right|$$

where  $S_{ij}(f)$  is the cross-spectrum of channels  $i$  and  $j$ . Cross-spectra were calculated by applying a Hanning taper to the data of each epoch, calculating the fast Fourier transform of the tapered data, and averaging over the epochs within a block.

### 2.2.2. Eye-movement conditions

Two conditions were used in the present research: (a) bilateral eye movement (EM) and (b) center control. The manipulations were identical to the bilateral and center conditions applied in Shobe et al. (2009) and modeled after Christman et al. (2003). Both manipulations were 30 s in duration, consisting of a circle 4° of visual angle in diameter that changed color every 500 ms. In the EM condition, the circle alternated between the left and right sides of the computer screen, separated by 27° of visual angle. In the center control condition, the circle remained fixed in the center of the screen.

### 2.2.3. Edinburgh Handedness Inventory (EHI; Oldfield, 1971)

Handedness was assessed using a revised version of the EHI, which included the 10 handedness items presented in Appendix II of Oldfield (1971). This modified version of the EHI has been used in numerous prior studies and is a reliable indicator of handedness (McMeekan, & Lishman, 1975). Participants must indicate their hand preference (always left, usually left, no preference, usually right, or always right) for each item (e.g., writing, throwing a ball, opening a lid on a jar, etc.). Responses are awarded a point value: always left: -10, usually left: -5, no preference: 0, usually right: 5, and always right: 10, and the point values are summed across the 10 items to generate a handedness score. Participants with scores of 80 or higher were categorized as consistent-handed and participants with scores of 75 or less were categorized as inconsistent-handed. This categorization for consistent versus inconsistent handedness groups was selected based on the definitions of consistent and inconsistent handedness provided in Prichard et al. (2013). We note that no participant in our sample had a negative handedness score because we only recorded data from right-handed participants, as is typical in neuroscience research.

### 2.2.4. Positive and negative affect schedule (PANAS; Watson, Clark, & Tellegen, 1988)

The PANAS is a 20-item assessment that is used to determine an individual's current mood state, providing scores on positive affect and negative affect subscales. Participants were asked to indicate the *extent you have felt this way during the past week* on a five-point Likert scale, ranging from 1, *very slightly or not at all*, to 5, *extremely*. Responses for the ten items in each sub-scale are summed to generate a positive and negative affect score.

### 2.2.5. PANAS-Short form (PANAS-SF; Thompson, 2007)

The PANAS-SF is a 10-item version of the PANAS. It is different from the PANAS in that the PANAS-SF uses only five items to construct the two subscales. Participants were asked to *focus on how you feel right now*. Responses were entered on a five-point Likert scale, ranging from 1, *very slightly or not at all*, to 5, *extremely*. The PANAS-SF has strong psychometric properties. In a series of validation studies conducted during the measure's inception, the PANAS-SF was shown to have high content and criterion validity, as well as strong test-retest reliability (Thompson, 2007).

### 2.2.6. Ten item personality Inventory (TIPI; Gosling, Rentfrow, & Swann, 2003)

This 10-item assessment is used to obtain scores on the five components of personality assessed by the Big-Five Personality Inventory: extraversion, agreeableness, conscientiousness, emotional stability, and openness to experiences. Two TIPI items are used to generate each of the component scores. The measure has high convergent validity, as well as high test-retest validity (Ehrhart et al., 2009; Gosling et al., 2003; Romero, Villar, Gómez-Fraguela, and López-Romero, 2012).

### 2.3. Procedure

The research protocol for this project was approved by Stockton University's Institutional Review Board. After providing written informed consent, participants completed the demographics form, followed by the PANAS and TIPI, which were counterbalanced. After the questionnaires, we applied the EEG net and resting-state EEG was recorded for four, 1-min blocks that alternated between eyes-closed and eyes-open recording. Participants were asked to sit in a relaxed position and to keep their minds free from other thoughts during the recording and were visually monitored for adherence to the eyes-closed or eyes-open block instructions, as well as drowsiness. Participants were then randomly assigned to the bilateral EM or control condition. Participants in the bilateral EM condition were instructed to track a circle on the computer screen by moving their eyes and not by moving their head. Participants in the control condition were instructed to watch the center circle. Adherence to the instructions was confirmed through experimenter observation. Immediately following the manipulation, participants began the post resting-state EEG recording identical to the pre resting-state recording. Immediately after the post recording, participants completed the PANAS-SF and the EHI.

Participants were then thanked and the session concluded.

## 3. Results

### 3.1. EEG data reduction and analysis overview

To prepare the power and coherence data for analysis, power and coherence values were averaged across the four resting-state blocks recorded prior to the manipulation to obtain pre power and coherence values and averaged across the four resting-state blocks recorded after the manipulation to obtain post power and coherence values. We calculated pre and post power and coherence scores separately for each frequency band. Difference scores (post – pre) were then calculated for each electrode site for power and for each electrode pair for coherence to isolate changes that occurred following the EM manipulation. All analyses were conducted as two-tailed tests and analyses including repeated-measures variables were Huynh-Feldt corrected. 95% confidence intervals are presented to clarify if the change scores were significantly different from zero. Although the theories surrounding the eye movements' effects on brain activity are not new, the direct exploration of the neural changes associated with bilateral eye movements has received little attention to date. Therefore, our analyses were exploratory and no alpha correction was performed.

### 3.2. Affect and personality

To determine if between group differences in affect and personality were present among conditions, we began by testing for differences in affect and personality prior to participation in the EM or control



manipulation. 2 (Condition: EM, control) × 2 (Handedness Group: consistent, inconsistent) univariate ANOVAs were conducted for the two affect variables (PANAS-Positive and PANAS-Negative) and the five personality measures (extraversion, agreeableness, conscientiousness, emotional stability, and openness to experiences). A significant main effect for Condition was observed for PANAS-Negative, with the EM condition showing higher PANAS-negative scores at the outset than the control condition (EM:  $M = 21.190$ ,  $SEM = 0.957$ ; Control:  $M = 17.862$ ,  $SEM = 0.980$ ),  $F(1, 82) = 5.907$ ,  $p = 0.017$ ,  $\eta_p^2 = 0.067$ . There was also a significant Condition by Handedness Group interaction for conscientiousness,  $F(1, 82) = 4.611$ ,  $p = 0.035$ ,  $\eta_p^2 = 0.053$ ; however, none of the pairwise comparisons was significant.

Considering the important role of bilateral eye movements in clinical applications, such as EMDR, we explored the change in positive and negative affect before versus after participants completed the eye-movement or control manipulation. Due to the difference in scale for the PANAS and PANAS-SF measures (20 items versus 10 items), we converted the raw scores to standardized scores for each variable. Change scores (post-pre) were compared using a 2 × 2 × 2 (Condition × Handedness Group × Affect: positive, negative) mixed model ANOVA. A significant Condition × Affect interaction was observed,  $F(1, 82) = 4.459$ ,  $p = 0.038$ ,  $\eta_p^2 = 0.052$ ; no other interactions or main effects were significant. Post hoc analyses revealed a significant difference between conditions for negative affect,  $F(1, 82) = 6.403$ ,  $p = 0.013$ ,  $\eta_p^2 = 0.072$ , with change scores for the EM condition showing a drop in negative affect pre to post that was significantly different from zero (EM:  $M = -0.392$ ,  $SEM = 0.197$ , 95% CI [-0.783, -0.001]), whereas change scores for the control condition, generally showed an increase in negative affect, but this increase was not significantly different from zero (Control:  $M = 0.320$ ,  $SEM = 0.201$ , 95% CI [-0.080, 0.720]). No differences were observed between conditions for positive affect change scores (EM:  $M = -0.098$ ,  $SEM = 0.169$ ; 95% CI [-0.435, 0.239]; Control:  $M = -0.151$ ,  $SEM = 0.173$ , 95% CI [-0.496, 0.194]),  $F(1, 82) = 0.048$ ,  $p = 0.828$ ,  $\eta_p^2 = 0.001$  (see Fig. 1a).

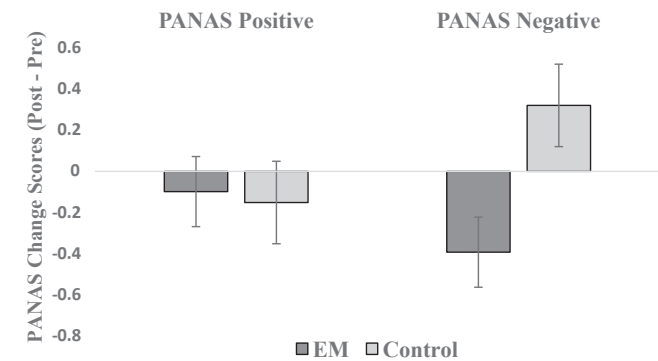


Fig. 1a. Positive and negative PANAS change scores by condition.

To more closely examine the differences in negative affect between EM and control conditions, we conducted a 2 × 2 (Condition × Time: Pre, Post) mixed model ANOVA on PANAS-Negative scores. Results included a significant Condition × Time interaction,  $F(1, 84) = 6.755$ ,  $p = 0.011$ ,  $\eta_p^2 = 0.074$ . Though post hoc analyses were not significant, there was a tendency for participants in the EM condition, who were more negative at the study's outset, to display a decrease in negative affect pre to post (Pre:  $M = 0.258$ ,  $SEM = 0.185$ ; Post:  $M = -0.134$ ,  $SEM = 0.155$ ),  $F(1, 41) = 4.033$ ,  $p = 0.051$ ,  $\eta_p^2 = 0.090$ . In contrast, participants in the control condition, who were less negative at the outset, instead, displayed a tendency toward an increase in negative affect pre to post that was not significant (Pre:  $M = -0.306$ ,  $SEM = 0.139$ ; Post:  $M = 0.014$ ,  $SEM = 0.188$ ),  $F(1, 41) = 2.491$ ,  $p = 0.122$ ,  $\eta_p^2 = 0.057$  (see Fig. 1b).

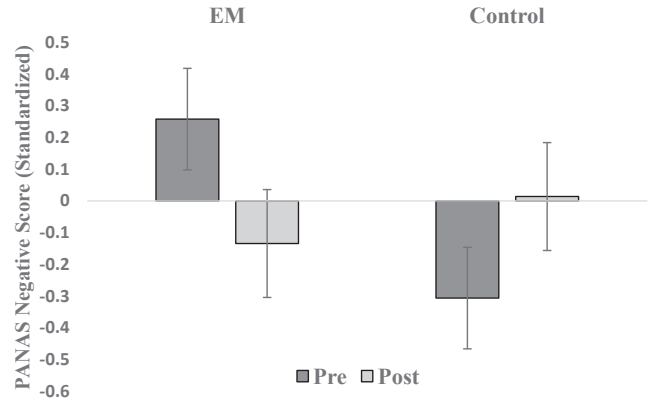


Fig. 1b. Pre- and post-manipulation PANAS – negative scores (standardized) by condition.

### 3.3. Inter-Hemispheric Interaction (IHI)

To test the IHI theory that bilateral eye movement alters communication between the hemispheres, we explored changes in power and coherence at the following homologous electrode sites: Fp1-Fp2, F3-F4, C3-C4, P3-P4, and O1-O2 (see Fig. 2a). Power and coherence changes were assessed separately for each frequency band.

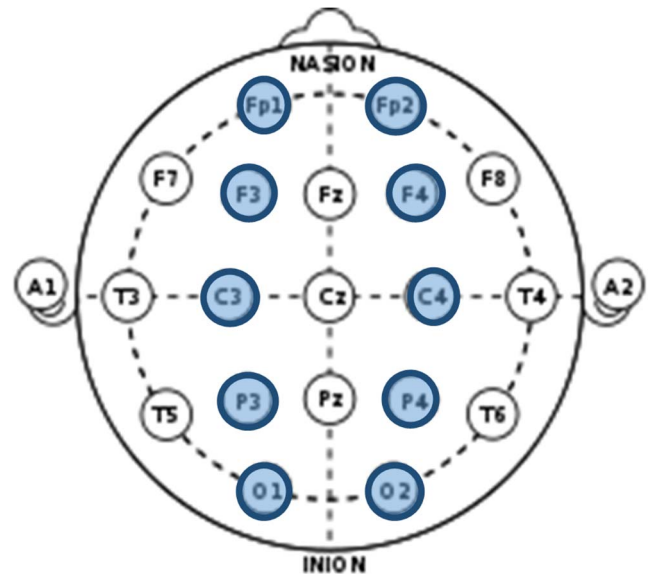


Fig. 2a. Electrode sites used to test the Interhemispheric Interaction (IHI) theory.

#### 3.3.1. Power

To analyze whether the EM manipulation and/or handedness influence the magnitude of spectral power from the hemispheres, we submitted power change scores for each frequency band to a 2 × 2 × 5 × 2 (Condition: EM, control × Handedness Group: consistent, inconsistent × Electrode Location: frontal pole, frontal, central, parietal, occipital × Hemisphere: left, right) mixed-model ANOVA. We observed significant findings for theta and beta frequency bands. For the theta frequency band, a main effect of handedness was observed for theta change scores,  $F(1, 82) = 8.072$ ,  $p = 0.006$ ,  $\eta_p^2 = 0.090$ . In this case, inconsistent handers showed a greater increase in theta power pre to post ( $M = 0.103$ ,  $SEM = 0.020$ ; 95% CI [0.064, 0.142]) than was displayed by consistent handers ( $M = 0.037$ ,  $SEM = 0.013$ ; 95% CI [0.012, 0.062]); in both handedness groups, theta change scores were significantly different from zero. Further, a significant

Condition  $\times$  Handedness interaction was detected,  $F(1, 82) = 5.811$ ,  $p = 0.018$ ,  $\eta_p^2 = 0.061$  (see Fig. 3). LSD post hoc comparisons comparing theta change scores among the four condition-group combinations revealed significant differences in theta change scores between inconsistent handers in the EM condition ( $M = 0.140$ ,  $SEM = 0.027$ ; 95% CI [0.086, 0.194]) and consistent handers in the EM condition ( $M = 0.018$ ,  $SEM = 0.018$ ; 95% CI [-0.017, 0.054];  $p < 0.001$ ) as well as consistent handers in the control condition ( $M = 0.056$ ,  $SEM = 0.018$ ; 95% CI [0.021, 0.091];  $p = 0.011$ ). No other between-group comparisons were significant. Although all groups showed mean increases in theta power pre to post, only the inconsistent handers in the EM condition and the consistent handers in the control condition had change scores that were significantly different from zero.

In addition to the theta effects, a significant main effect for handedness was observed for change scores in the beta frequency band (see Fig. 4),  $F(1, 82) = 4.090$ ,  $p = 0.046$ ,  $\eta_p^2 = 0.048$ . As in the theta frequency band, inconsistent handers showed a greater increase in beta change scores from pre to post than consistent handers (Consistent:  $M = 0.013$ ,  $SEM = 0.003$ , CI 95% [0.007, 0.019]; Inconsistent:  $M = 0.024$ ,  $SEM = 0.004$ , CI 95% [0.015, 0.032]), with both increases significantly different from zero. However, for beta, the potential main effect for condition and the condition by handedness group interaction were not significant.

Interestingly, no significant main effects or interactions were observed for electrode location or hemisphere in any of the frequency bands. Taken together, these findings indicate that the EM manipulation does not preferentially activate one hemisphere more than the other, so has no effect on increasing or decreasing activation asymmetries. However, EMs may enhance the theta power increase for inconsistent handers. Further, inconsistent handers exhibited an increase in beta power pre to post regardless of condition, suggesting that inconsistent handers may exhibit greater fluctuations in EEG signal over time than consistent handers.

### 3.3.2. Coherence

To determine if the EM manipulation and/or handedness group corresponded to differences in synchronization between the hemispheres, we submitted coherence change scores to a  $2 \times 2 \times 5$  (Condition  $\times$  Handedness Group  $\times$  Electrode Location) mixed model ANOVA for each frequency band. In this case, coherence reflected the synchronization in electrical activity between homologous electrode pairs (e.g., Fp1-Fp2) and was used as a measure of the coordination in electrical activity between the hemispheres. Significant differences in changes scores reflecting coherence between the hemispheres were observed only for the delta frequency band. Within delta there was a significant Condition  $\times$  Handedness  $\times$  Electrode Location interaction,  $F(4, 82) = 2.644$ ,  $p = 0.046$ ,  $\eta_p^2 = 0.031$ . Post hoc comparisons for each electrode pair (i.e., Fp1-Fp2, F3-F4, C3-C4, P3-P4, and O1-O2) revealed a significant Condition  $\times$  Handedness interaction for coherence change scores between C3 and C4 electrodes,  $F(1, 82) = 4.218$ ,  $p = 0.043$ ,  $\eta_p^2 = 0.049$ . However, LSD post hoc analyses comparing all four condition-handedness groups failed to reveal significant differences in change scores among groups ( $p > 0.05$ ).

### 3.4. Attention control (AC)

To test Lyle and Martin's (2010) attentional control (AC) hypothesis, change scores for power and coherence were explored for frontal and posterior electrode sites over regions of the executive attention network (see Fleck, Kuti, Brown, Mahon, & Gayda-Chelder, 2016; Sauseng, Klimesch, Schabus, & Doppelmayr, 2005). Frontal sites included F7, F3, Fz, F4, and F8, and posterior sites included T5/P7, P3, Pz, P4, and T6/P8 (see Fig. 2b).

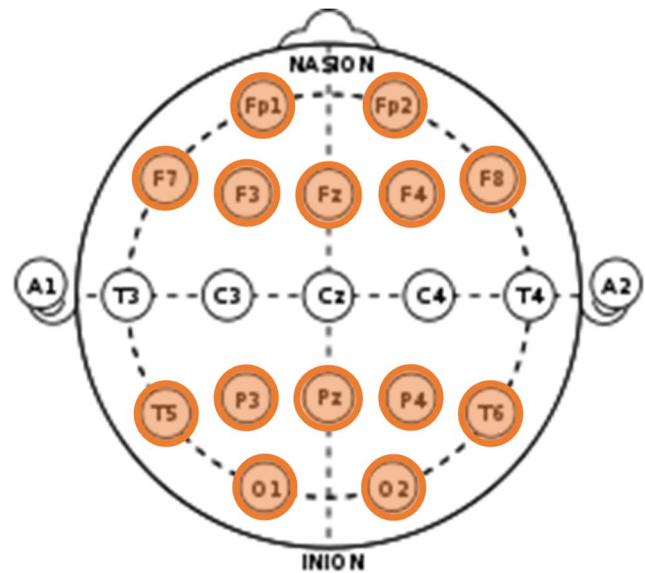


Fig. 2b. Electrode sites used to test the attentional control hypothesis.

#### 3.4.1. Power

To determine if the EM manipulation and/or handedness group corresponded to power changes over frontal and posterior electrode sites, power change scores were submitted to a  $2 \times 2 \times 2 \times 5$  (Condition  $\times$  Handedness Group  $\times$  Anterior-Posterior Region: anterior, posterior  $\times$  Electrode Location: left lateral, left medial, midline, right medial, right lateral) mixed model ANOVA for each frequency band. Similar to the IHI electrode configuration, significant power findings for the AC electrode configuration were restricted to theta (see Fig. 3), and beta (see Fig. 4) frequency bands, with a similar pattern of main and interaction effects to those observed for IHI. For theta power, we observed a handedness main effect, in which inconsistent handers displayed a greater increase in theta power change scores ( $M = 0.097$ ,  $SEM = 0.018$ , 95% CI [0.061, 0.133]), than was revealed by consistent handers ( $M = 0.028$ ,  $SEM = 0.012$ , 95% CI [0.005, 0.051]),  $F(1, 82) = 10.314$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.112$ , with mean change scores differing significantly from zero for both groups. Similarly, a significant Condition  $\times$  Handedness interaction was observed for theta change scores,  $F(1, 82) = 6.606$ ,  $p = 0.012$ ,  $\eta_p^2 = 0.075$ . LSD post hoc analyses comparing the four condition-handedness groups revealed significant differences in mean change scores between inconsistent handers in the EM condition ( $M = 0.133$ ,  $SEM = 0.025$ , 95% CI [0.082, 0.183]) and both consistent handers in the EM condition ( $M = 0.008$ ,  $SEM = 0.017$ , 95% CI [-0.025, 0.041];  $p < 0.001$ ) and consistent handers in the control condition ( $M = 0.048$ ,  $SEM = 0.016$ , 95% CI [0.015, 0.080],  $p = 0.006$ ). No other between group comparisons were significant. Mean change scores for inconsistent handers in the EM condition, inconsistent handers in the control condition ( $M = 0.062$ ,  $SEM = 0.026$ , 95% CI [0.010, 0.114]) and consistent handers in the control condition all differed significantly from zero.

In the beta frequency band, inconsistent-handed participants ( $M = 0.021$ ,  $SEM = 0.004$ , 95% CI [0.013, 0.028]) displayed a greater increase in beta change scores than was present in consistent-handed participants ( $M = 0.009$ ,  $SEM = 0.002$ , 95% CI [0.004, 0.014]),  $F(1, 82) = 7.166$ ,  $p = 0.009$ ,  $\eta_p^2 = 0.080$ , with both mean change scores significantly different from zero. No significant main or interaction effects were observed for Anterior-Posterior or Lateral-Medial variables in any frequency band. Taken together, these power findings support the conclusions from our analyses using the IHI electrode array. As in IHI, our analyses using our AC electrode array provided evidence for a

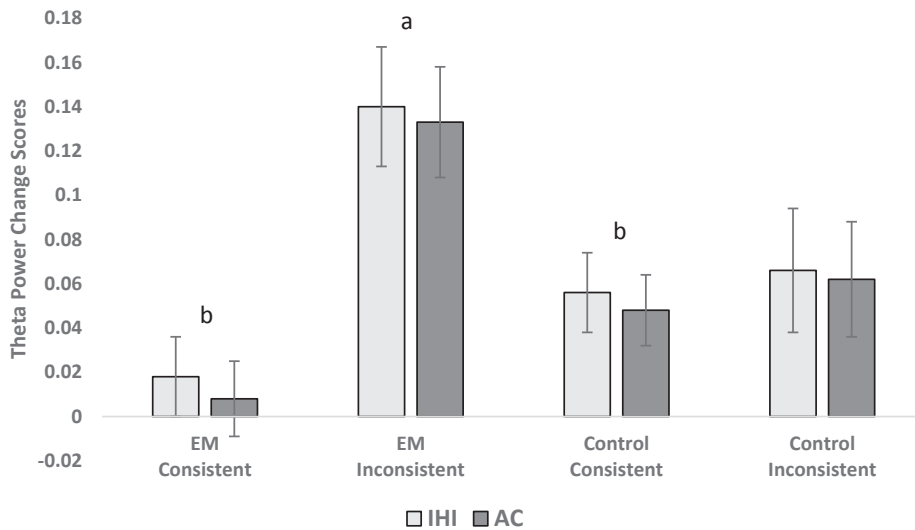


Fig. 3. Mean change in theta power (post – pre) for condition/handedness groups. The error bars reflect one standard error of the mean.

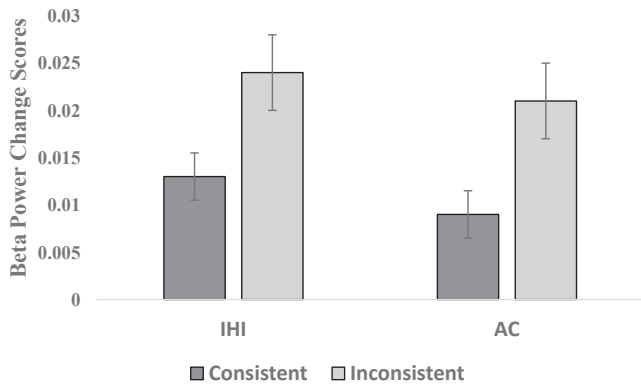


Fig. 4. Mean change in beta power (post – pre) by handedness group. The error bars reflect one standard error of the mean.

greater increase in beta power for inconsistent- than consistent-handed participants. In addition, a condition by handedness group interaction was again observed exclusively in the theta frequency band, in which exposure to the EM manipulation served to enhance the increase in theta power changes scores for inconsistent-handed participants.

### 3.4.2. Coherence

To test whether the EM manipulation and/or handedness group were connected to differences in coherence change scores for the synchronization of spectral activity over frontal and posterior regions of the executive attention network, two mean coherence change scores were calculated. The first set of coherence change scores was calculated using electrode pairs within frontal or posterior regions, with the calculations performed separately for each hemisphere: left frontal (Fp1, F3, and F7), right frontal (Fp2, F4, and F8), left posterior (T5/P7, P3, and O1), and right posterior (T6/P8, P4, and O2). The second set of change scores was calculated using frontal-posterior electrode pairs, in which one electrode was in the frontal region and the other in the posterior region (e.g., F3-P3), establishing mean coherence change scores for the following regions: left anterior-posterior, midline anterior-posterior, and right anterior-posterior. Regional coherence change scores and anterior-posterior coherence change scores were then explored in separate analyses.

To begin, a  $2 \times 2 \times 2 \times 2$  (Condition  $\times$  Handedness  $\times$  Region: anterior, posterior  $\times 2$  Hemisphere) mixed model ANOVA was conducted to assess the influence of the EM manipulation on regional coherence. For the delta frequency band, there was a significant main

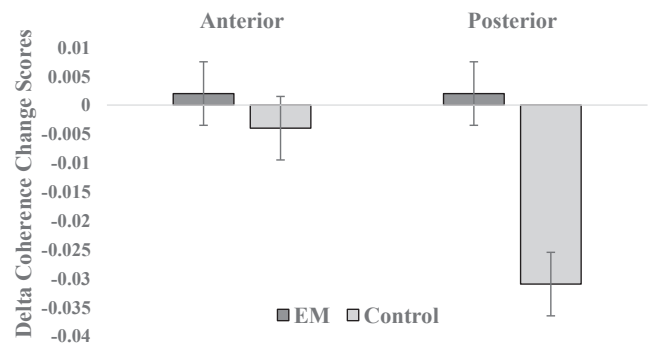


Fig. 5. Mean change in delta coherence by condition for anterior and posterior brain regions – AC electrode configuration. The error bars reflect one standard error of the mean.

effect for condition,  $F(1, 82) = 12.082, p = 0.001, \eta_p^2 = 0.128$ . In this case, mean delta change scores for the control condition were significantly different from zero and decreased pre to post ( $M = -0.0171, SEM = 0.0038, 95\% \text{ CI } [-0.025, -0.010]$ ), whereas mean delta change scores for the EM condition did not differ significantly from zero ( $M = 0.0017, SEM = 0.0039, 95\% \text{ CI } [-0.006, 0.009]$ ). In addition, we observed a significant Condition  $\times$  Region interaction,  $F(1, 82) = 6.564, p = 0.012, \eta_p^2 = 0.074$  (see Fig. 5). Further exploration of this interaction revealed a significant difference in coherence change scores over posterior electrode sites between the EM ( $M = 0.002, SEM = 0.006, 95\% \text{ CI } [-0.010, 0.014]$ ) and control conditions ( $M = -0.031, SEM = 0.006, 95\% \text{ CI } [-0.043, -0.019]$ ),  $F(1, 82) = 14.463, p < .001, \eta_p^2 = 0.15$ . As in the main effect for condition, the decrease in mean delta change score for the control condition was significantly different from zero whereas the mean delta change score did not differ from zero in the EM condition. There was no difference in delta coherence change scores between the EM ( $M = 0.002, SEM = 0.005, 95\% \text{ CI } [-0.007, 0.011]$ ) and control ( $M = -0.004, SEM = 0.005, 95\% \text{ CI } [-0.013, 0.005]$ ) conditions over anterior electrode sites,  $F(1, 82) = 0.723, p = 0.398, \eta_p^2 = 0.009$ . These findings indicate a significant decrease in delta coherence pre to post for the control condition over the posterior regions of the brain, but the absence of a significant change in coherence for the EM condition.

In a second step, a  $2 \times 2 \times 3$  (Condition  $\times$  Handedness  $\times$  Frontal-Posterior Location: left hemisphere, midline, right hemisphere) mixed model ANOVA was conducted to compare coherence between frontal-posterior regions for each frequency band. We observed a marginally-

significant condition effect in the alpha frequency band,  $F(1, 82) = 3.872$ ,  $p = 0.05$ ,  $\eta_p^2 = 0.045$ . In this case, although the mean change score was higher in the control group ( $M = 0.009$ ,  $SEM = 0.007$ , 95% CI  $[-0.005, 0.024]$ ) than the EM group ( $M = -0.010$ ,  $SEM = 0.007$ , 95% CI  $[-0.024, 0.004]$ ), neither mean change score differed significantly from zero. Analyses comparing the change in alpha coherence between conditions for left-hemisphere, midline, and right-hemisphere locations, produced a significant difference between conditions for frontal-posterior coherence change at the midline,  $F(1, 84) = 4.309$ ,  $p = 0.041$ ,  $\eta_p^2 = 0.049$  (see Fig. 6). Mean change scores revealed a decrease in frontal-posterior alpha coherence in the EM condition ( $M = -0.014$ ,  $SEM = 0.011$ , 95% CI  $[-0.037, 0.009]$ ), but an increase in frontal-posterior coherence in the control condition ( $M = 0.017$ ,  $SEM = 0.012$ , 95% CI  $[-0.007, 0.040]$ ); neither change score over the midline was significantly different from zero. No differences were detected between conditions for the left hemisphere,  $F(1, 84) = 2.655$ ,  $p = 0.107$ ,  $\eta_p^2 = 0.031$ ; or the right hemisphere,  $F(1, 84) = 1.064$ ,  $p = 0.305$ ,  $\eta_p^2 = 0.013$ .

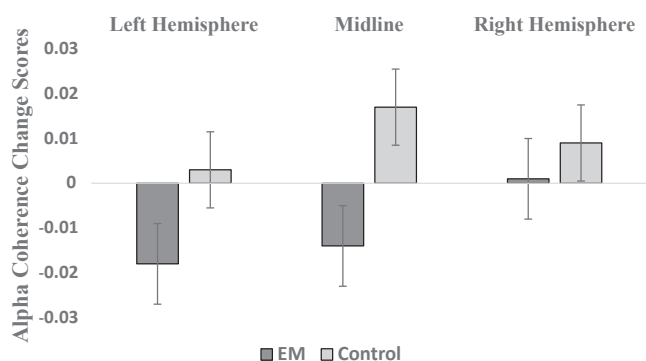


Fig. 6. Mean change in alpha coherence between anterior and posterior brain regions by condition for left hemisphere, midline, and right hemisphere locations – AC electrode configuration.

Considered together, the coherence results stemming from the analysis of the AC electrode array revealed a significant difference between EM and control conditions for delta coherence change scores over the posterior region of the brain, with the control condition decreasing in delta pre to post.

### 3.5. Covariates

Because of the pre-manipulation difference between conditions in PANAS negative scores, we also ran analyses using PANAS positive and PANAS negative scores as covariates. In doing so we explore the potential role of PANAS pre scores, PANAS post scores, and PANAS change scores as covariates in the design. None of the variables was a significant covariate in any of the analyses. Further, there were no changes in the results for power or coherence change scores in any of the frequency bands; analyses that were significant in our initial run remained so with the addition of the PANAS variables.

## 4. Discussion

The goal of the present research was to explore the impact of bilateral eye movements on resting-state EEG in order to test two existing theories underlying the eye movements' effects, the Interhemispheric Interaction (IHI) theory (Christman et al., 2003) and the Attentional Control (AC) theory (Lyle & Martin, 2010). We recorded participants' resting-state brain activity with EEG before and after they completed 30 s of bilateral eye movements or a center-control manipulation. To assess changes in brain activity, we determined the change in EEG power and zero-phase-lag coherence, a measure of synchronization of

activity among regions. To test the main tenets of each theory, IHI and AC, we selected an electrode array that best captured the neural effects proposed by each theory. For IHI, we selected the array to capture potential fluctuations in brain activity between the hemispheres; and for AC, we selected an array to capture potential changes in brain activity over frontal and posterior brain regions, areas of the executive attention network. Although our explorations of IHI and AC theories failed to provide unequivocal support for either theory, we observed significant changes in EEG coherence, which suggest that bilateral eye movements influence activity in the brain at rest. These changes in resting-state EEG may offer insight into the mechanisms that underlie the beneficial effects of bilateral eye movements on cognition and in the reduction of PTSD symptomology via EMDR.

Our comparison of participants' PANAS scores, measured before versus after the EM manipulation, demonstrated a change in behavior associated with the completion of bilateral eye movements. Participants in the EM condition showed a significant decrease in negative PANAS scores pre to post. This reduction of negative mood coincides with the findings of Yaggie et al. (2015) who reported a decrease in the vividness of negative memories following exposure to bilateral eye movements. Although inconsistent-handed participants have exhibited a flexible style of emotion regulation in prior research, including lower need for closure and reduced emotional stability (see Shobe, 2014, for a review), we failed to find a significant main effect or interaction involving handedness group.

In general, our analyses revealed significant differences in EEG oscillations based on condition (eye-movement versus control) and handedness (consistent versus inconsistent). Differences in absolute power were observed between handedness groups, with inconsistent handers showing an increase in absolute power pre to post for theta and beta frequency bands. For theta, however, the increase in power was greatest for inconsistent handers who had completed the bilateral eye-movement manipulation. Of importance, the power findings for the theta and beta frequency bands were consistent regardless of which electrode array was examined, IHI or AC, and failed to indicate unique differences by brain region. Though handedness was not the principal grouping variable in our design, we believe the changes in EEG power that emerged between handedness groups over time reflect a difference in flexibility of resting-state brain activity based on handedness, with inconsistent handers having greater potential for change. If so, this flexibility in neural response over time may align with the superior performance of inconsistent handers over consistent handers on cognitive tasks requiring cognitive flexibility (see Prichard et al., 2013, for a review).

In addition to our findings for EEG power, we observed significant differences in EEG coherence between eye-movement and control groups, for the delta frequency band, along with a condition main effect that approached significance in the alpha frequency band. Although delta coherence decreased pre to post for the control condition over posterior electrode sites, no significant change in delta coherence was evident for the eye-movement condition. We suggest that the stability of delta coherence over time in the eye-movement condition may reflect a beneficial effect of sustained executive attention stemming from the eye-movement manipulation. However, we acknowledge that we did not directly test the influence of bilateral eye movements on attention; our work only assessed the impact of the EM manipulation on mood, as measured through the change in PANAS scores. Therefore, it is possible that the stability of delta coherence over time in the EM condition may be related to interest, arousal, or another factor not mentioned here.

Prior research has associated delta oscillations with sustained concentration during executive function, along with the capacity to direct attention to external stimuli (e.g., Buschman & Miller, 2007; Knyazev, 2012). Harmony (2013) observed consistent increases in delta power over the frontal regions of the brain when participants performed tasks that required sustained concentration, such as mental calculation tasks and the Go/No-Go task. In addition, Buschman and Miller (2007)



reported greater frontal-posterior coherence in the slower frequency bands (i.e., delta and theta) during a visual detection task for top-down but not bottom-up trials.

Prior research has reported positive correlations between delta oscillations and sensory processing networks (e.g., posterior attention network; Jann, Kottlow, Dierks, Boesch, & Koenig, 2010). For example, Lakatos et al. (2008) reported an increase in delta phase locking when participants processed stimuli that were presented in an ordered and predictable pattern. In their research, delta oscillations were recorded in the primary visual cortex of monkeys as they were presented with rhythmic light flashes. When the monkeys detected a consistent pattern in the stimulus stream, delta entrainment that matched the rhythm of the stimulus stream was associated with improved selective attention to the target stimulus. In our research, the manipulations presented in both the eye-movement and control conditions were rhythmic and predictable. It is feasible that both conditions could have influenced delta connectivity. However, we contend that the added motor component in the eye-movement condition (i.e., moving the eyes horizontally, from side to side) necessitates greater selective attention than that required by the control condition, as is suggested by the SIRE theory. As a result, engaging in bilateral eye movements may provide a mechanism to help individuals maintain selective attention over time.

In addition to group differences in delta coherence, we observed a decrease in alpha coherence pre to post in the eye-movement condition, that was marginally significant when compared to controls. This decrease was greatest between frontal and posterior brain regions over the midline. Prior research has reported a positive relationship between alpha power and activation in the default mode network (DMN), along with an inverse relationship between alpha power and activity in the frontoparietal attention network (FPAN), which is engaged during task-directed cognition and sensory processing (Knyazev, 2013; Mantini et al., 2007). In addition, desynchronization of activity in the alpha frequency band has been associated with increased attention to external stimuli (see Benedek, Bergner, Könen, Fink, & Neubauer, 2011; Klimesch, 1999). Together, prior research demonstrates an important relationship between the alpha frequency band and the regulation of attention. The decrease in frontal-posterior alpha coherence over the midline in the present research may indicate that engaging in bilateral eye movements increases cognitive readiness by engaging the FPAN and disengaging the DMN. Although it is possible that the trend toward a decrease in alpha coherence in the EM condition does stem from a shift from DMN to FPAN network engagement, source localization methods are needed to conclusively demonstrate that the change in alpha coherence observed in the present research indeed reflects this shift in network activity.

In sum, the differences in change scores for delta and alpha coherence between the eye-movement and control conditions suggest that the eye-movement manipulation may influence cognition by supporting enhanced executive attention. If this is the case, the changes we observed in resting-state coherence may offer support for the Attentional Control Hypothesis proposed by Lyle and Martin (2010; see also Edlin & Lyle, 2013).

Our coherence findings align with some of the findings obtained in prior research exploring the impact of bilateral eye movements on brain activity. Similar to our findings, Propper et al. (2007) and Samara et al. (2011) failed to find an increase in interhemispheric power or coherence following the eye-movement manipulation, though their exploration of the neural changes following bilateral eye movements specifically targeted changes in activation between the hemispheres. In subsequent research, Keller et al. (2014) observed an increase in right frontal delta coherence in participants who engaged in bilateral eye movements while recalling a positive episodic memory from childhood. Important distinctions exist, however, between Keller et al.'s method and the method applied in the present research. We asked participants to perform an eye-movement manipulation and recorded their post resting-state EEG activity as they were sitting in a relaxed state, with

their minds free from thought. In contrast, Keller et al. exposed participants to bilateral eye movements as they retrieved a positive memory, and then recorded their resting-state EEG activity as participants reflected on their current thoughts and emotions and provided ratings about their retrieved childhood memory. As a result, and as noted by Keller et al., the increased right-frontal delta coherence was likely associated with participants' attention to their positive emotional states stemming from the memory retrieval task. Thus, we suggest that the ability of the eye-movement condition to maintain posterior delta coherence over time in the present research is evidence of a change in brain activity that results from participants' performance of repetitive bilateral eye-movements.

In addition to the coherence results, we observed differences between consistent- and inconsistent-handed participants over time in EEG power for theta and beta frequency bands, with inconsistent handers presenting a more substantial increase in theta and beta power pre to post than was indicated by consistent handers. Prior research has supported the stability of EEG power and coherence over time for both resting-state and task-directed cognition (McEvoy, Smith, & Gevins, 2000), with high within-subject reliability for EEG power and coherence in multiple test paradigms (e.g., Corsi-Cabrera, Galindo-Vilchis, del-Río-Portilla, Arce, & Ramos-Loyo, 2007; Gudmundsson et al., 2007). Although power and coherence have been identified as consistent EEG signatures over time, frequency-specific fluctuations have been identified. Corsi-Cabrera et al. (2007) found more fluctuation across EEG recording sessions over a 9-month period for theta and beta power, than for the other frequency bands, suggesting a greater potential for fluctuation over time in some EEG frequency bands. In addition, researchers have suggested that about 60% of the resting-state EEG signal at any point in time stems from stable trait properties (Hagemann, Hewig, Seifert, Naumann, and Bartussek (2005)). Although Hagemann et al. did not speculate on which trait variables are most significant in influencing resting-state EEG, there is certainly room for individual differences to influence the recorded EEG signal.

Our findings suggest that handedness may be an important variable in one's potential for EEG signal change. Although we know of no prior research that has reported differences in the fluctuation of EEG oscillations over time based on handedness, researchers have identified differences in resting-state EEG between handedness groups. Propper, Pierce, Geisler, Christman, and Bellorado (2012) observed decreased resting-state brain activation (increased alpha power) over the left frontal region in inconsistent-handed versus consistent-handed participants. If inconsistent handers do possess increased malleability in their EEG signals, particularly in theta and beta frequency bands, this flexibility may contribute their enhanced performance on tasks such as episodic memory and cognitive flexibility, as observed in prior research (see Prichard, et al., 2013, for a review). Theta and beta frequencies have been associated with performance in a variety of cognitive domains in which inconsistent-handed individuals demonstrate superior performance, including episodic memory, attention, and semantic integration (e.g., Klimesch, Schimke, & Schwaiger, 1994; Ray & Cole, 1985; Rowland, Meile, & Nicolaidis, 1985).

We acknowledge that the lack of condition by handedness interactions in our electrophysiological findings may be difficult to reconcile with behavioral findings that typically report cognitive enhancements for consistent handers following bilateral eye movements, but the absence of positive effects for inconsistent handers. However, we suspect that the differences in resting-state coherence between conditions may only interact with handedness-related differences in cognition during cognitive processing itself (see Lyle et al., 2012). For example, if the difference in delta coherence between conditions is related to differences in executive attention, increasing executive attention should result in increased task performance if an individual must complete a task in a weaker cognitive domain. Episodic memory and creativity are tasks in which consistent handers typically display poorer performance than inconsistent handers at baseline. As a result, engaging executive

attention through bilateral eye movements may allow a consistent-handed individual to adopt more effective strategies during memory retrieval or creativity. However, inconsistent handers already excel on memory and creativity tasks at baseline, perhaps due to factors other than strategy use (e.g., increased corpus callosum thickness and greater access to processing in the right hemisphere; Prichard et al., 2013). Therefore, engaging executive attention through bilateral eye movements may lead inconsistent handers to adopt novel strategies during memory retrieval and creativity tasks that are not advantageous during cognitive processing.

We argue that the increases in theta and beta power pre to post in inconsistent handers and the decrease in delta coherence pre to post in the control condition are largely independent effects. However, the unique EM-handedness interaction for the change in theta power does require additional consideration. We suspect that the significant increase in resting-state theta power for inconsistent handers may be relevant in the deleterious behavioral effects observed in inconsistent handers in prior research (Lyle et al., 2008, 2012). As noted by Lyle et al. (2012), differences in baseline brain activity between handedness groups may result in different patterns of brain activity when these individuals are exposed to bilateral eye movements. Research that directly explores differences in baseline brain activity between handedness groups would clarify potential differences in resting-state activity associated with handedness.

Admittedly, the effects on cognition following bilateral eye movements are typically small and, thus, may be difficult to detect consistently in research. In an adversarial collaboration study, Matzke et al. (2015) failed to find improved episodic memory performance in a list-learning paradigm for participants exposed to bilateral eye movements. In addition, Samara et al. (2011) were only able to detect an improvement in episodic memory performance during a word recall task for emotional list items. Matzke et al. propose that the presence of inconsistent findings in the literature likely stems from problems in data analysis and/or issues in study design. We suggest that unmeasured individual difference variables may also play an important role. As reviewed in Edlin et al. (2015), researchers inconsistently measure and report handedness across studies, a practice that is particularly problematic considering the significant differences in EEG fluctuations over time between handedness groups that we observed in the present research. Thus, if handedness has a larger impact on brain activity over time than can stem from the eye-movement manipulation, the ability to detect cognitive outcomes resulting from the eye-movement manipulation will depend heavily on researchers' measurement and control of individual differences variables.

There are several potential limitations with the present research that should be considered when interpreting our findings. First, we explored participants' resting-state brain activity for effects stemming from the bilateral eye-movement manipulation. It is probable that comparing brain activity between eye-movement and control conditions during task-directed cognition will reveal different results. We also acknowledge the disparity in the number of participants who were categorized as consistent versus inconsistent handers based on their scores on the EHI (i.e., scores of 80 or higher as consistent, and scores of 75 or less as inconsistent). In both the eye-movement and control conditions, only 30% of group members were inconsistent handers. However, most of our participants were women (86%), and our percentages are similar to those reported by Prichard et al. (2013), who indicated that approximately 60% of right-handed females are consistent handers. Increasing the percentage of male participants, and including left-handed participants, would increase the proportion of inconsistent-handed sample members in future research. Finally, because our findings were reported without an alpha correction, our findings should be considered exploratory.

In conclusion, our exploration of the resting-state EEG activity recorded before and after we exposed participants to the bilateral eye-movement or center-control manipulation revealed several important

differences in brain activity between groups. Coherence changes in the delta and alpha frequency bands support the influence of bilateral eye movements on resting-state brain activity and may support the influence of bilateral eye movements on attention regulation. Although unexpected, we also observed an increase in theta and beta power in inconsistent handers pre to post, a possible indicator of increased neural flexibility in inconsistent handers.

Our research findings reveal several veins of research that are needed moving forward. First, because bilateral eye movements affect cognition and mood, but have a limited influence on resting state brain activity, it is important to understand the relationship between bilateral eye movements' effects on resting-state EEG and task-related EEG activity. Further, the interpretation of our results above suggests that bilateral eye movements may influence the frontoparietal attention and/or the dorsal attention resting-state networks (see Mantini et al., 2007). Thus, research that explores the impact of bilateral eye movements on different attention processes (e.g., executive versus orienting) would help to elucidate the eye movements' effects. Exploration of the impact of bilateral eye movements on cognition has been limited primarily to episodic memory and creativity, with some exploration of other domains, such as visual search and attention. Examination of the eye movements' influence on other cognitive domains will be important to clarify the manipulation's effects. Finally, as we observed in the present research, individual difference variables, such as handedness, may be important in the potential influence of bilateral eye movements, and should be explored in detail in future research.

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