A functional near-infrared spectroscopy study of the effects of configural properties on sustained attention

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Abstract

Forty-five participants performed a vigilance task during which they were required to respond to a critical signal at a local feature level, while the global display was altered between groups (either a circle, a circle broken apart and reversed, or a reconnected figure). The shape in two of the groups formed a configurative whole (the circle and reconnected conditions), while the remaining shape had no complete global element (broken circle). Performance matched the results found in the previous experiments using this stimulus set, where a configural superiority effect was found to influence accuracy over time. Physiological data, measured using functional near-infrared spectroscopy, revealed elevated activation in the right pre-frontal cortex compared to the left pre-frontal cortex during the task. Additionally, bilateral activation was found in the conditions that formed configurative wholes, while hemispheric differences over time were found in the condition that did not. These findings suggest that configural aspects of stimuli may explain why non-typical laterality effects have been found in similar research.

Introduction

The task of monitoring ones' immediate environment for rarely occurring or critical stimuli is a requirement for many people in everyday life, particularly for those in workplaces where a large amount of information is received. Psychologists refer to this process as vigilance or sustained attention (Davies & Parasuraman, 1982; Warm, 1984). A consistent finding in vigilance research is that sustained attention evokes right-hemisphere lateralization in the brain in right handed individuals. Specifically, blood flow and blood oxygenation is elevated in the right hemisphere compared to the left hemisphere during vigilance, an outcome which has been found using functional magnetic resonance imaging (fMRI), positron emission tomography (PET), transcranial Doppler sonography (TCD), and functional near-infrared spectroscopy (fNIRS; Berman & Weinberger, 1990; Buchsbaum et al., 1990; Cohen et al., 1988; Helton et al., 2007; Hitchcock et al., 2003; Lewin et al., 1996; Parasuraman, Warm & See, 1998; Shaw et al., 2009; Stroobant & Vingerhoets, 2000; Warm, Matthews & Parasuraman, 2009; see Helton et al., 2010 and Warm et al., 2012 for overview). Moreover, research with commissurotomized (split-brain) patients demonstrates improved performance during vigilance tasks when signals are presented to the right hemisphere as opposed to the left hemisphere (Diamond, 1979a; 1979b).

Although sustained attention often results in a right hemisphere lateralization effect, it is also possible that stimuli characteristics, such as object feature hierarchy, may influence hemispheric lateralization. Visual objects are ordered in a hierarchical fashion, where larger objects are composed of a number of smaller features or shapes, which in turn could themselves also be composed from even smaller elements. The small components of an object are commonly referred to as local features, while the large components are commonly referred to as global features. A common finding in local-global feature discrimination literature is that the right hemisphere shows elevated levels of activity and blood oxygenation during global feature discrimination, while the left hemisphere shows elevated levels of activity and blood oxygenation during local feature discrimination (Flevaris, 2010; Lux et al., 2004; Manjaly et al., 2007; Stone & Tesche, 2009; Van Kleeck, 1989; Weissman & Woldorff, 2005; Yamaguchi, Yamagata & Kobayashi, 2000). These investigations tend to adopt more perception-based paradigms, where prolonged temporal search is not a central component of the task. Local-global feature discrimination during vigilance tasks has not received as much investigation; however recent research has begun to address this.

Those investigations which have been undertaken in this area yield patterns of hemodynamic response and performance which differ from those from purely sustained attention or perception-based tasks. For example, investigations using perception-based approaches to local-global feature discrimination commonly reveal a global precedence; where global objects are more easily discernible than local objects (Kimchi, 1992; Lamb & Roberston, 1990; Navon, 1977). Under sustained attention conditions however, tasks in which local feature discrimination is required have been found to result in faster reaction times compared to those that require global feature discrimination; a local precedence effect (de Joux et al., 2013; de Joux et al., 2015a; Helton, Hayrynen & Schaeffer, 2009). These investigations also reveal differing trends over time, with quadratic trends observed in local discrimination (performance initially decreases, but the later improves with time on task), compared with a more traditional linear decrement observed in global feature discrimination (performance consistently decreases with time on task). These performance differences are theorized to be partially due to corresponding differences in patterns of hemodynamic response found during the tasks. Local feature discrimination is found to result in higher levels of bilateral activation over time compared to global feature discrimination, where more right hemisphere lateralization is found. This may be the result of global feature processes (right hemisphere dominant) and sustained attention processes (right hemisphere dominant) combining to place higher demand on the right hemisphere. In contrast, local feature discrimination processes (left hemisphere dominant) combined with sustained attention processes (right hemisphere dominant) do not produce the same demand placement on one hemisphere; instead, demand is spread across both hemispheres. This bilateral activation may allow more cognitive resources to be recruited towards the task, resulting in the differing performance trends observed over time.

While differences in performance and cerebral activation were observed in the de Joux et al. (2013; 2015a) and Helton et al. (2009) investigations; specifically that local feature discrimination displayed greater bilateral activation over time which resulted in superior performance compared to global feature discrimination; the stimuli used in these investigations were of a relatively simple nature. Nonetheless, they do raise questions as to how configural properties of more complex stimuli may influence task performance and cerebral activity by evoking local-global feature discrimination, and whether investigations that deviate from traditional cerebral activation patterns found during vigilance tasks may in some part be due to the requirement to engage local-global discrimination processes. Funke et al. (2010; 2012) and Nelson et al. (2014), for example, employed a task designed to simulate radar detection. In this task, participants were required to monitor four arrows which were positioned on a background circle, and were orientated in the same clockwise or anti- clockwise direction. Participants were required to respond when one of those arrows was orientated in the opposite direction to the other three. Using TCD (cerebral blood flow velocity) and fNIRS (blood oxygenation) as measurements of cerebral hemodynamic activity, the usual right hemisphere lateralized patterns associated with vigilance tasks were not observed. While the right hemisphere did show an elevated level of activity in comparison to the left hemisphere, increased bilateral activation was found to occur during the tasks (left hemisphere trends matched those of the right hemisphere). A possible explanation for these non-typical laterality findings is that the task requirements evoke, at least in part, local-feature processing, which results in increased bilateral activation over time rather than a unilateral right hemisphere bias. It should also be noted that while increased bilateral activation was observed, oxygen saturation increased linearly over time.

De Joux et al. (2015b) explored this by extending the Funke et al. (2010; 2012) investigations to examine performance differences between stimuli which had varying configurative properties. Three global shapes were used: a circle, a reversed and broken apart circle, and a reconnected shape (see Figure 1 for examples). The circle shape provided a similar configuration to that used by Funke and colleagues. The reversed broken circle shape consisted of the same overall level of visual information in terms of surface area; however by splitting and reversing the circle, the overall global shape no longer formed a complete and connected figure. The reconnected shape was the reversed broken circle shape that had been extended at the break points, which resulted in the object reconnecting with itself to form a full global shape. This shape retained some aspects of the broken shape, in that the reversed nature of the object remained the same; however, it also shared some aspects with the circle shape, specifically in that it formed a configurative whole. In terms of local-global features, the circle and reconnected shapes were considered to be local targets on a global object, while the broken shape was considered to be targets on separate shapes. The results revealed that the broken group showed impaired performance compared to the circle and reconnected groups. Furthermore, the circle and reconnected groups had highly similar performance trends throughout the task. These findings were considered to be indicative of a configural superiority effect, in which stimuli that are encoded in the brain as a full or complete global form are processed more efficiently than those that do not (see also, Bennett & Flach, 2011; Pomerantz & Kubovy, 1986; Pomerantz & Pristach, 1989; Pomerantz, Sager & Stoever, 1977). Proctor et al. (2004) also noted that signals are more accurately detected when target objects were presented on a meaningful background, for which it is suggested an underlying mechanism is that different visual processing systems are utilized in the processing of background and foreground visual information (Julesz, 1978). This may provide an explanation for the observed trends. Additionally, traditional vigilance decrement patterns were not observed in this experiment. While this study did not employ a measure of hemodynamic response, it was suggested that this may have been partially due to an increase in bilateral activation, as reported in the Funke et al (2010; 2012) investigations.

In the current experiment, the investigation presented in de Joux et al. (2015b) is extended by employing a measure of cerebral hemodynamic activity during the task. Cerebral hemodynamic response has been closely linked to neural activity during sustained attention tasks (Moore & Cao, 2007; Raichle, 1998). Studies have found that this response occurs in a number of areas, most commonly the right inferior parietal regions, basal ganglia, right intralaminar region of the thalamus, reticular formation, and the inferior prefrontal cortex (Kinomura, Larsson, Gulyas, & Roland, 1996; Langner et al., 2012; Langner & Eickhoff, 2013; Ogg et al., 2008; Parasuraman, Warm, & See, 1998). The current research focuses on activity in the inferior prefrontal cortex for two reasons. First, this area has been the focus of similar research investigating configural properties (de Joux et al., 2013; de Joux et al., 2015a; Helton et al., 2009). Second, investigations as to the neural underpinnings of the configural superiority effect have found the 'higher' regions of the brain (i.e. the prefrontal cortex) to be crucial in the formation of full Gestalt figures (Biederman, 1987; Riesenhuber & Poggio, 1999).

The specific instrumentation used in the current investigation is functional near-infrared spectroscopy (fNIRS). The fNIRS uses wavelengths of light to measure oxygenated and deoxygenated haemoglobin. From this, a level of relative oxygen saturation is calculated. These measurements have been found to correlate with the BOLD response found in both fMRI (Kleinschmidt et al., 1996; Steinbrink et al., 2005; Strangman et al., 2002) and EEG measures of cerebral activity (Meltzer, Negishi, Mayes, & Constable, 2007; Moosmann et al., 2003). It has been established by previous research that tissue oxygenation increases with task demands (Gratton & Fabiani, 2007), which raises the prospect of tissue oxygenation being a result of resource demands. The fNIRS presents a useful tool for researchers to investigate cerebral activity during tasks by providing quieter, less restricting, and less costly imaging when compared to fMRI and PET. It should be noted that fNIRS measures cerebral activation through relative oxygen saturation. This should not be confused with other measures of cerebral hemodynamic activity, which use other metrics. TCD, as used in the Funke et al. (2010; 2012) investigations for example, measures cerebral blood flow velocity in the cerebral arteries which transport the majority of blood in the brain. As an area of the brain becomes active, blood flow to that area is elevated in order to remove by-products of that activity (CO_2, for example). This is distinctly different from fNIRS, which may represent the transport of resources to the active area, rather than transport of waste away from the active area.

The current experiment also extends the total experiment length (32 minutes vs 20 minutes) in order to further examine the possibility of passive perceptual learning influencing trends. There is potential that passive perceptual learning, where participants may passively learn search strategies throughout the vigil in order to become more efficient over time, influenced the trends found in the previous experiment; a possibility that was noted by the authors. It has been suggested in previous experiments that this improvement due to passive perceptual learning is greater in conditions that have a lower level of performance initially (Head & Helton, 2015). It was suggested that the previous improvement in the broken condition may have been due to this effect. It would be unlikely, however, that performance would show a continuous improvement given an extended period of time. With an extended vigil length, it may be possible to see an initial improvement in performance due to this effect, before seeing a more traditional vigilance decrement due to resource demands. The extended vigil length also brings the study more in line with other previous research which has used fNIRS, where task lengths are typically longer than 20 minutes (Boyer, Cummings, Spence & Solovey, 2015; de Joux et al., 2013; de Joux et al., 2015a; Hancock, 2015; Shaw, Nguyen, Satterfield, Ramirez & McKnight, 2016).

De Joux et al. (2015b) found similar performance (measured in hits, false alarms and A’ scores) between the reconnected and circle conditions. Therefore it was hypothesized that the circle and reconnected conditions would show similar patterns of performance over time using the same metrics, with no significant differences between them. Additionally, it was expected that these two groups would display a higher level of performance compared to the broken condition, again similar to the previous results. The broken condition showed a slight improvement in performance over time in the previous experiment, although this was likely due to the broken condition performing at such a level that a significant decrease was not possible. It was expected that this previously observed increase would be mitigated by the longer vigil of the current experiment that placed greater demands on sustained attention resources. Additionally, as the broken condition is likely to be performing at a near-floor level, no significant vigilance decrement is expected in this condition.

Despite behavioural changes over time not being expected, we did expect that there would be differences in cerebral activation. We expected that these differences would be due to differences in visual processing requirements, and are separate from workload related oxygenation trends (de Joux et al., 2013). Although previous investigations do find increased bilateral activation (i.e., similar trends in both hemispheres) in studies requiring more local feature discrimination, the right hemisphere still shows elevated levels of cerebral oxygenation comparative to the left hemisphere. This was expected to be replicated in the current experiment, given the sustained attention component of the task. However, in regard to differential changes in hemispheric activity with time on task, the circle and reconnected groups are expected to show increased bilateral activation rather than differential hemispheric activity changes due to the configural properties of those displays (Funke et al., 2010; Funke et al., 2012; Nelson et al., 2014). This is interpreted as both hemispheres displaying similar trends of activation over time, regardless of the elevated right hemisphere activation overall.

Specifically, we expect that the circle and reconnected conditions should display similar patterns of cerebral activation over time, due to the aforementioned configural superiority effect found with these two objects. These displays should evoke higher levels of local processing and recruit the left-hemisphere more than a non-configural display. The broken condition should display a pattern of activation unlike that which is found in the circle and reconnected conditions, because the configural superiority effect should not occur in shapes which are not perceived as a whole. We expect the broken condition to show evidence of lesser activation of the left-hemisphere than in the conditions with configural displays.

Method

Participants

Participants were 45 students (21 males, 24 females) from the University of Canterbury in Christchurch, New Zealand. This meant that there were 15 participants in each group. While this is a modest number of participants, it is similar to participant numbers found in similar investigations (de Joux et al., 2013; de Joux et al., 2015a; Martinez et al., 1997; Ossowski, Malinen & Helton, 2011; Todorow, DeSouza, Banwell & Till, 2014). Participants' ages ranged from 19 to 33 years (M = 23.9 years, SD = 2.3). All participants were right handed, which was indicated by the participant and confirmed through observation of hand use while signing the consent form, completion of questionnaires and key responses during the vigilance task. All participants had normal or corrected-to-normal vision.

Materials

The 45 participants were assigned at random to either a circle, broken or reconnected object vigil. Participants were tested individually in a windowless laboratory room. Participants were seated approximately 40 cm from a 270 mm x 340 mm video terminal display, which was positioned at the eye level of the participant. Participants were unrestrained throughout the duration of the task; however they were instructed to minimize any unnecessary head movements which could displace the fNIRS sensors, as well as any sudden body movements which could result in the fNIRS sensor units being moved. All participants were briefed regarding the task, and informed of the fNIRS and its function, before they provided their written consent to undertake the study.

Each participant was fitted with the fNIRS instrumentation, which was the Nonin Near-Infrared Cerebral Oximeter equipped with Equanox sensors. The sensors were placed at Fp1 and Fp2 positions (using standard 10/20 configuration for EEG placement; see Figure 1) on the forehead, and secured using a customized adjustable headset. The Fp1 and Fp2 positions were chosen because they are commonly used during clinical use of the fNIRS (Kim et al, 2000; Scheeren, Schober & Schwarte, 2012), as well as aligning with previous investigations involving vigilance tasks (de Joux et al., 2013; de Joux et al., 2015a; Helton et al., 2007; Punwani et al., 1998). Additionally, investigations into the configural superiority effect have found the prefrontal cortex to be crucial in the formation of Gestalt figures (Biederman, 1987; Riesenhuber & Poggio, 1999). The Nonin Near-Infrared Cerebral Oximeter measures cerebral oxygen saturation (rSO2). This is calculated by determining the relative amounts of oxyhemoglobin (O2HB) and deoxyhemoglobin (HHb) in each hemisphere. The Nonin Near-Infrared Cerebral Oximeter requires two sensor pads (specifically the Equanox Advance Model 8004CA pads) to be attached to the forehead of the participant throughout the entirety of the task. The Equanox pads consist of two light emitters and two light detectors, with each detector receiving light from each light emitter. The emitters to detector distances are 20mm and 40 mm. Four different wavelengths of light are used (725 nm, 755 nm, 805 nm and 875nm). Readings are obtained at 3-second intervals.

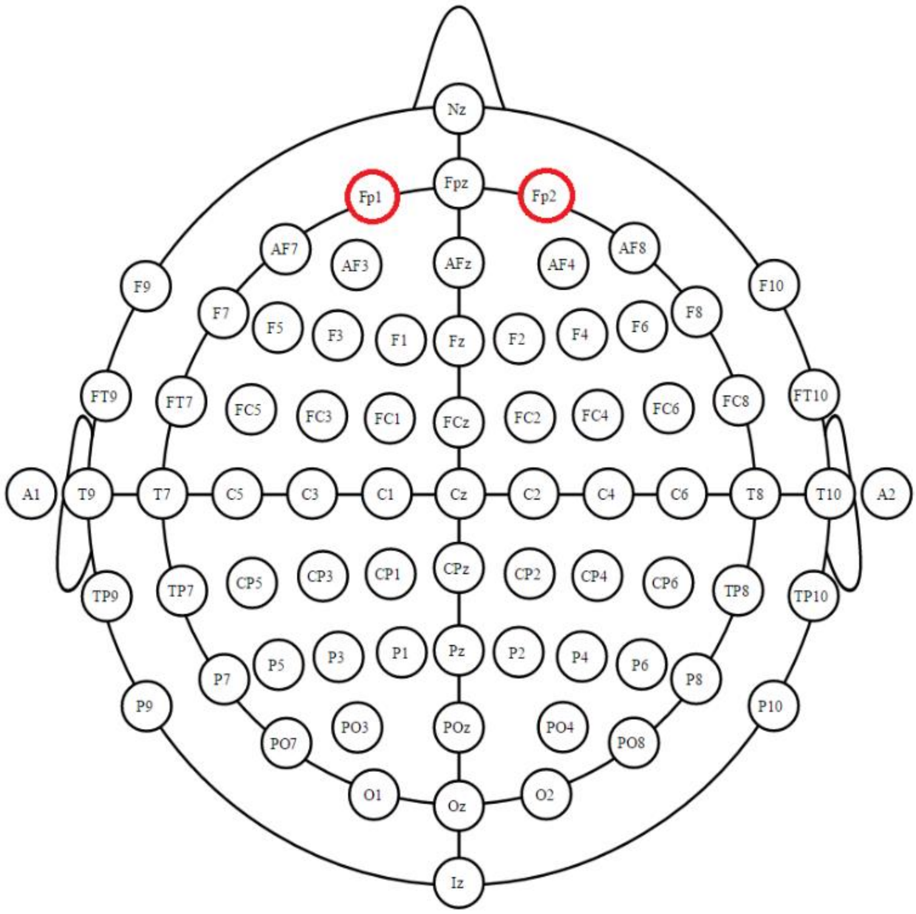


Figure 1. Standard 10/20 configuration (shown from above the head, nose at the top of the image) showing the Fp1 and Fp2 positions where the sensors were held.

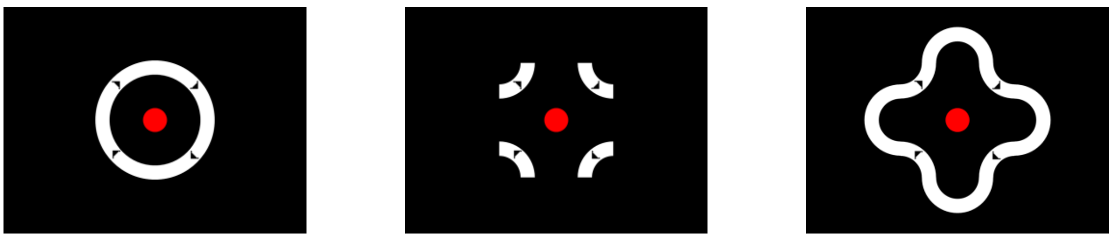


Figure 2. Examples of the visual stimuli.

Participants performed a go/no-go task using objects which were composed of different configural properties (see Figure 2). These properties consisted of a set of four black arrows placed on a white background shape, which was itself encompassing a solid red central circle that acted as a central fixation point. The black arrows act as the local component of the overall object, while the white shapes are considered the global component. The screen position and size (75 mm x 80 mm) of the black arrows was uniform across all conditions, while the white global shape was manipulated. Three manipulations of the white global shape were presented: enclosed circle (circle); disconnected "broken" circle (broken); and reconnected "broken" circle (reconnected). The width of the white line was kept the same across all conditions (120 mm), while the overall size of the global objects differed slightly (circle = 10 cm x 10 cm; broken = 9.5 cm x 9.5 cm; reconnected = 15 cm x 15 cm).

Each participant was also required to complete an 11-item self-report stress scale before and after the task. This scale has been used in previous studies (Blakely, 2014; Hancock, 2015; Wilson, de Joux, Finkbeiner, Russell, & Helton, 2016), with factor analysis revealing a 3-factor solution of; distress, task engagement, and mind-wandering.

Procedure

Upon entering the experiment room, each participant completed the questionnaire by relating each item to their activities in the previous 5-10 minute period. This was to serve as a baseline subjective rating for that participant. Upon completion of the pre-test questionnaire, participants were assigned to one of the three experimental conditions described above, before being fitted with the fNIRS. Once correctly fitted with the device, each participant undertook a five minute period in which their baseline fNIRS readings were recorded. During this period participants were instructed to maintain a state of "relaxed wakefulness" while seated in front of a blank display. They were to remain silent, minimize body movement, and maintain regular breathing patterns, similar to how they would react in the vigil. Cerebral oxygenation during the final minute of this baseline period was used as a baseline index (Aaslid, 1986). The final minute of the 5 minute period was used as baseline to allow time for participants to become accustomed to the device attached to their forehead and for their rSO2 levels to stabilize.

Participants were shown a brief instructional screen to outline the task, before performing a 2-minute practice period. The task required participants to monitor brief displays of the stimuli and respond whenever one of the four black arrows was orientated in an opposite direction to the other three black arrows (target). The opposite target could occur at any of the 4 positions shown in Figure 2. Results from previous experiments using these stimuli revealed that the orientation of the arrows had no effect on responses. Therefore the arrows were clockwise, while the critical target arrow was pointed anti-clockwise. Responses were made by pressing the central space bar on a computer keyboard. During each trial the red central circle alone was first displayed for 500 ms, followed by the target shape being displayed for 500 ms, before the red central circle was again displayed for 1000 ms. It was during this 1500 ms period that participant responses were recorded. Each individual trial was 2000 ms in duration. There were 60 trials per trial period, and each period was 2 minutes in duration. Participants completed 16 trial periods in total, which were completed consecutively with no breaks between periods. The overall time including all fNIRS baseline testing, trial periods, and practice periods was 39 minutes, with 34 minutes allocated to the vigil itself. Distracter and target stimuli were presented in random order with a target display probability of 13.33 percent, and a neutral display probability of 86.66 percent in both practice and main trials. In total, 8 trials per period contained target objects. Participants were not informed of this target probability.

Immediately following completion of vigil task, the fNIRS was removed from the participants' forehead. Participants were then asked to complete the post-test questionnaire. Following this, participants were debriefed about the experiment and its purpose before receiving compensation for their time.

Results

Performance

For each participant the proportion of correct detections (hits), the proportion of false alarms (false alarms) and the signal detection theory metric A' (A Prime) was calculated for each period of watch. A' is a metric used in signal detection theory to measure perceptual sensitivity (Stanislaw & Todorov, 1999). Also for each individual, the reaction time to each correctly detected target was averaged for each period of watch. Average reaction times for each participant for each period of were then subjected to a log10 transformation, as recommended by Maxwell and Delaney (2004) regarding treatment of reaction times during such tasks. A 3 (shape: circle, broken, and reconnected) by 16 (periods of watch) repeated measures ANOVA with orthogonal polynomial contrasts was performed for each of the above metrics (Keppel & Zedeck, 2001; Ross et al., 2014; Ruxton & Beauchamp, 2008). Orthogonal contrasts are a more powerful statistical test compared to repeated-measures ANOVA, which is the more commonly used statistical analysis method in vigilance research (Rosenthal & Rosnow, 1985; Rosnow & Rosenthal, 1996; Rosenthal, Rosnow & Rubin, 2000). Such tests avoid problems related to the assumption of sphericity and are a direct test of trend differences (changes over periods of watch) between conditions. This allows direct tests for specific trends of interest. For the pre-planned orthogonal polynomial contrasts we limited the contrasts to the linear and quadratic trends. This is in line with the analysis performed in the de Joux et al., (2015b) research. Specifically, we wanted to test that the broken condition was indeed significantly different from the reconnected and circle conditions; and that the two complete global shape conditions (circle and reconnected) we performing at similar levels in line with hypotheses. Both the trend analyses and the more commonly used repeated measures ANOVA results are reported for interested readers.

Hit Proportions

In the case of hit proportions, there were no significant linear trends, $F(1, 42) = .23$, p = .637, $\eta_p{}^2 = .005$, or quadratic trends, $F(1, 42) = 3.72$, p = .060, $\eta_p{}^2 = .081$, for periods of watch. Nor were there any significant period by shape linear, $F(2, 42) = .12$, p = .891, $\eta_p{}^2 = .005$, or quadratic trends, $F(2, 42) = .68$, p = .511, $\eta_p{}^2 = .031$. There was, however, a significant main effect for shape, $F(2, 42) = 10.14$, p = .000, $\eta_p{}^2 = .326$. Additionally, a series of planned comparison analyses were performed. This revealed a significant difference between the combined circle and reconnected groups versus the broken group, $F(1, 42) = 20.27$, p = .000, $\eta_p{}^2 = .325$. There were no significant differences between the circle and reconnected conditions alone, $F(1, 42) = .00$, p = .956, $\eta_p{}^2 = .023$. Hit proportions are displayed in Figure 3.

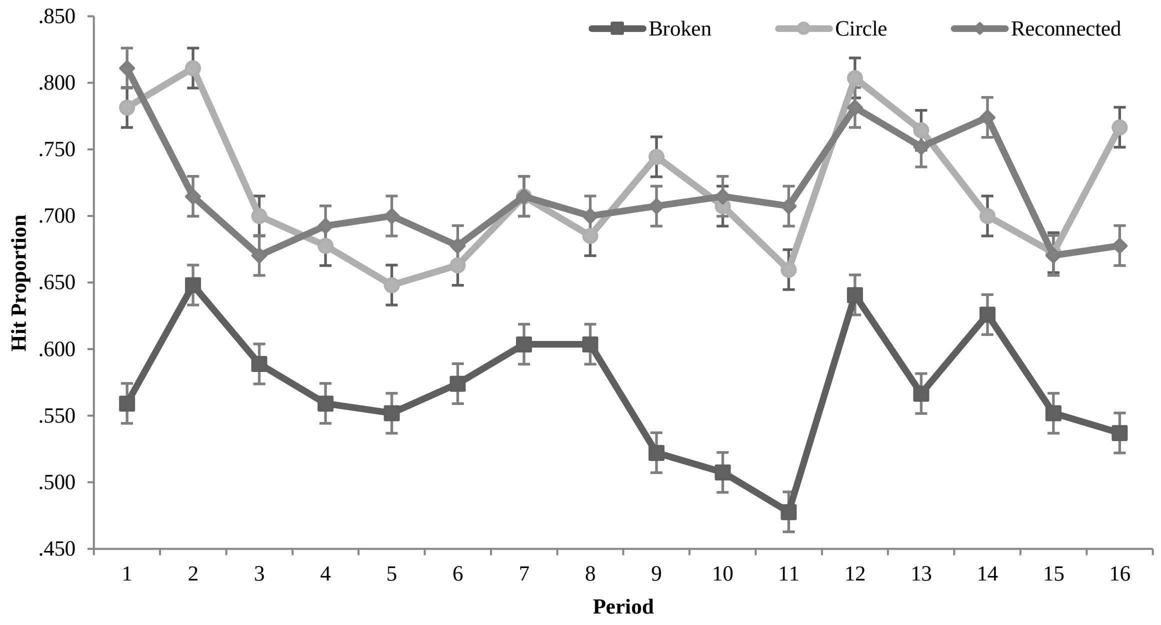


Figure 3. Mean proportions of hits over 16 periods of watch. Error bars depict standard error.

False Alarms

For false alarm proportions, there was a significant linear trend, $F(1, 42) = 30.41$, p = .000, $\eta_p{}^2 = .420$, and significant quadratic trend, $F(1, 42) = 17.42$, p = .000, $\eta_p{}^2 = .293$, for time on task, with false alarms decreasing over time. There were no significant shape by period linear, $F(1, 42) = .12$, p = .891, $\eta_p^2 = .006$, or quadratic interaction trends found, $F(1,42) = 1.04$, p = .362, $\eta_p^2 = .047$. Additionally, there was no significant main effect for shape, $F(2, 42) = 1.47$, p = .241, $\eta_p^2 = .065$. Mean proportion of false alarms are presented in Figure 4. All conditions exhibit a decrease in false alarms over time, with little difference between shapes. It is important to note that overall the false alarm rate was low in all groups (M = .024).

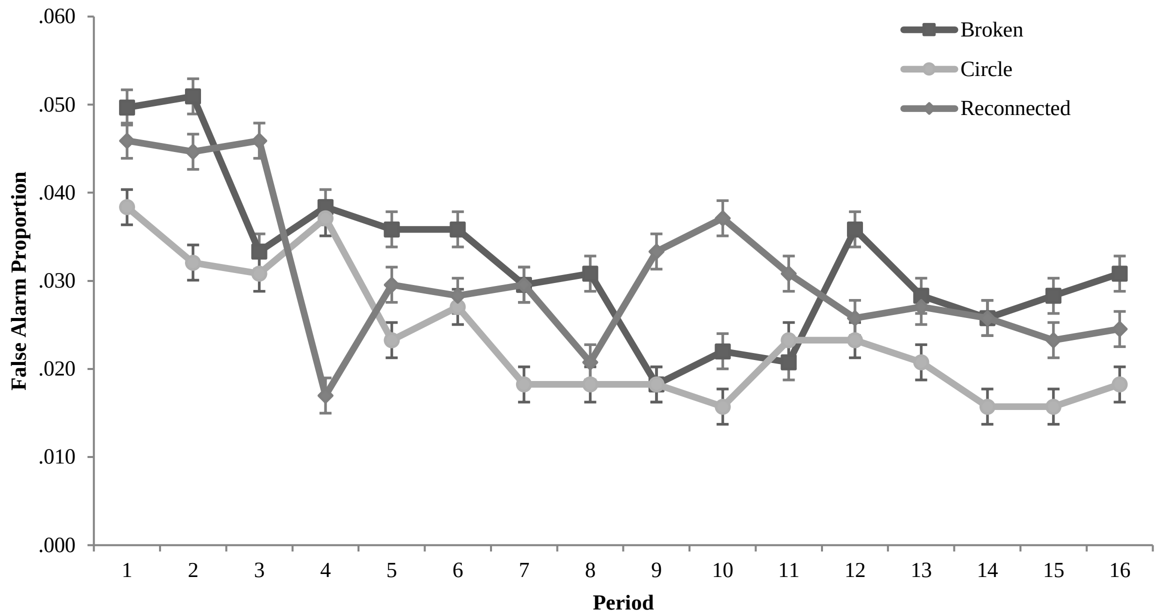


Figure 4. Mean proportions of false alarms over 16 periods of watch. Error bars depict standard error.

A' Scores

In the case of A' scores, there was no significant linear trend, $F(1, 42) = .58$, p = .450, $\eta_p^2 = .014$, or quadratic trend, $F(1, 42) = .98$, p = .329, $\eta_p^2 = .023$, for period of watch. Nor were there any shape by period linear, $F(2, 42) = .02$, p = .985, $\eta_p^2 = .001$, or quadratic trends, $F(2, 42) = .86$, p = .429, $\eta_p^2 = .040$. Similar to hit proportions, there was a significant main effect for shape, $F(2, 42) = 10.20$, p = .000, $\eta_p^2 = .327$. As with the analysis for hit proportions, a series of pre-planned orthogonal comparison analyses were performed. These revealed a significant difference between the combined circle and reconnected groups versus the broken group, $F(1, 42) = 20.27$, p = .000, $\eta_p^2 = .326$, with the combined circle and reconnected groups showing greater target sensitivity. There was no significant difference in target sensitivity between the circle and reconnected conditions, $F(1, 42) = .14$, p = .715, $\eta_p^2 = .023$. Mean A' scores are presented in Figure 5.

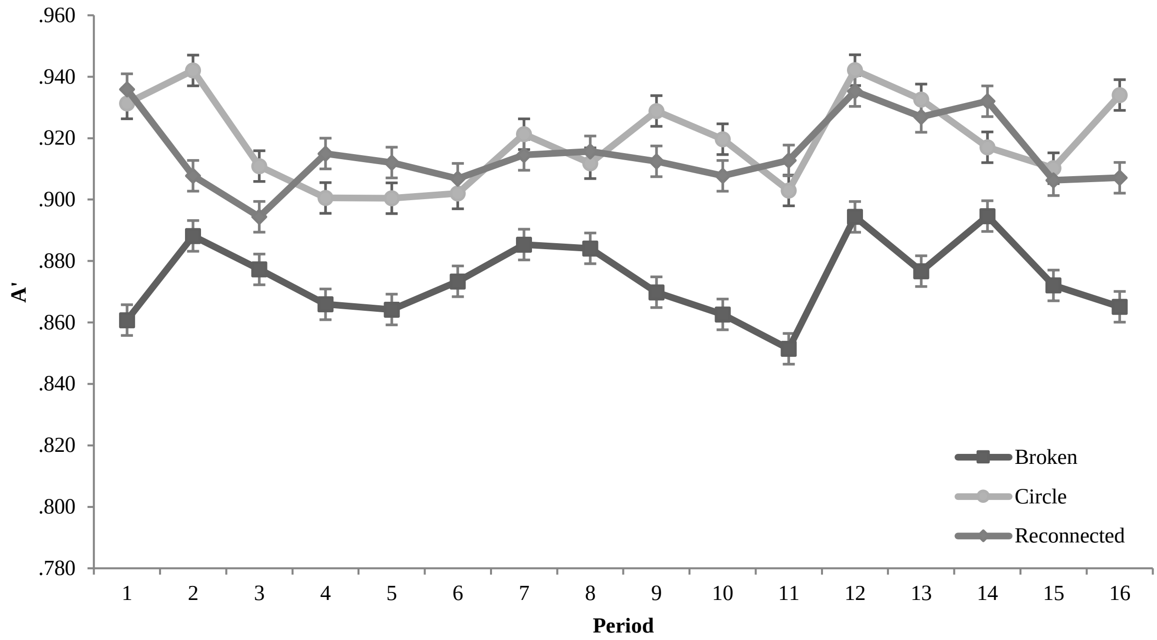


Figure 5. Mean *A'* scores over 16 periods of watch. Error bars depict standard error.

Reaction Times

For the log10 transformed reaction times, there was no significant linear trend, $F(1, 42) = 1.16$, p = .29, $\eta_p^2 = .027$, for periods of watch, however there was a significant quadratic trend, $F(1, 42) = 15.43$, p = .000, $\eta_p^2 = .269$. Here, reaction times increased initially overall, before becoming quicker in the later periods of watch. There was no period by shape linear trend, $F(2, 42) = .32$, p = .727, $\eta_p^2 = .015$, nor quadratic trend, $F(2, 42) = .51$, p = .605, $\eta_p^2 = .024$. The omnibus test revealed a significant main effect for shape, $F(2, 42) = 7.61$, p = .002, $\eta_p^2 = .266$. A series of pre-planned orthogonal contrasts were performed. This analysis revealed a significant difference between the combined circle and reconnected condition versus the broken condition, $F(1, 42) = 10.53$, p = .002, $\eta_p^2 = .200$. There was also a significant difference found between the circle and reconnected conditions, $F(1, 42) = 4.69$, p = .036, $\eta_p^2 = .100$, however there was no significant difference between the reconnected and broken conditions, $F(1, 42) = 2.98$, p = .091, $\eta_p^2 = .066$. A final contrast comparing the combined reconnected and broken conditions versus the circle condition revealed a significant difference, $F(1, 42) = 12.23$, p = .001, $\eta_p^2 = .226$. These results suggest the circle condition has the fastest reaction times overall, followed by the reconnected and broken conditions respectively. Mean log10 reaction times scores are presented in Figure 6.

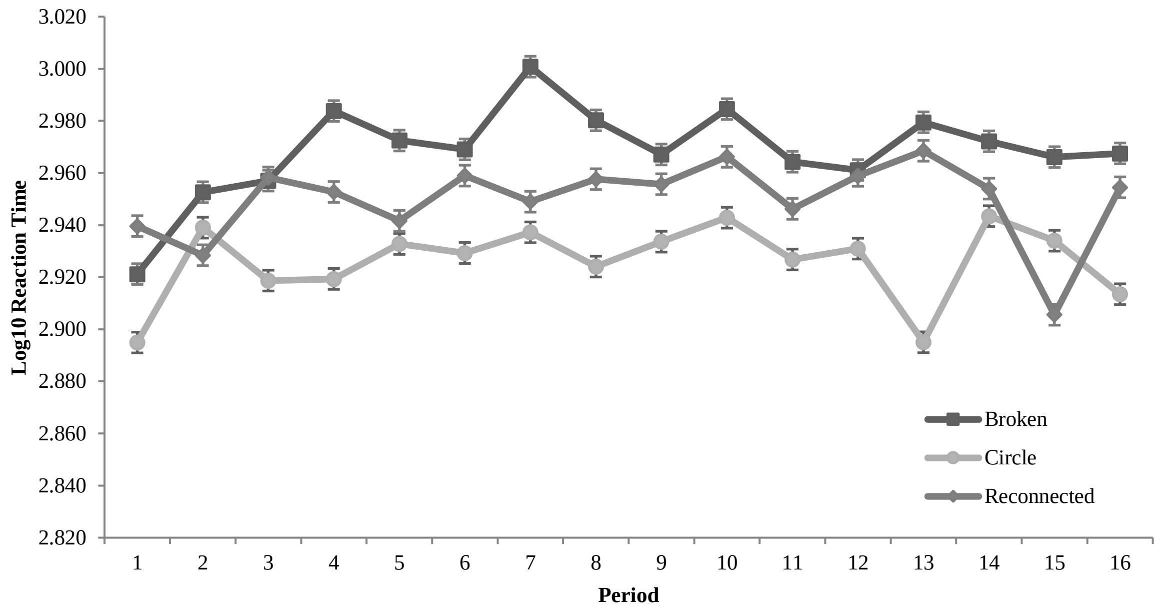


Figure 6. Mean Log10 reaction times over 16 periods of watch. Error bars depict standard error.

Physiology

In line with previous studies that have used fNIRS for vigilance research, a relative measure of regional oxygen saturation (rSO2) was used during analyses (de Joux et al., 2013; de Joux et al., 2015a; Helton et al., 2007; Yoshitani, Kawaguchi, Tatsumi, Kitaguchi, & Furuya, 2002). These scores are based on the percentage change relative to the individuals' resting baseline. A score of 0 indicates zero change from the baseline. These rSO2 change scores were examined using a 3 (shape: circle, broken, and reconnected) x 2 (hemisphere: right or left) x 16 (period of watch) mixed between-within repeated measures ANOVA. Similar to performance scores, orthogonal polynomial contrasts were also employed to assess specific trends of interest.

Regarding total oxygenation, while there was no significant linear trend, $F(1, 42) = 3.33$, p = .075, $\eta_p{}^2 = .073$, there was a significant quadratic trend for period, $F(1, 42) = 30.81$, p = .000, $\eta_p{}^2 = .423$, with rSO2 initially decreasing over the first four periods of watch before increasing over the final four periods of watch. This is shown in Figure 7. There were no significant differences between groups in regards to total oxygenation, nor were there any significant period by group effects.

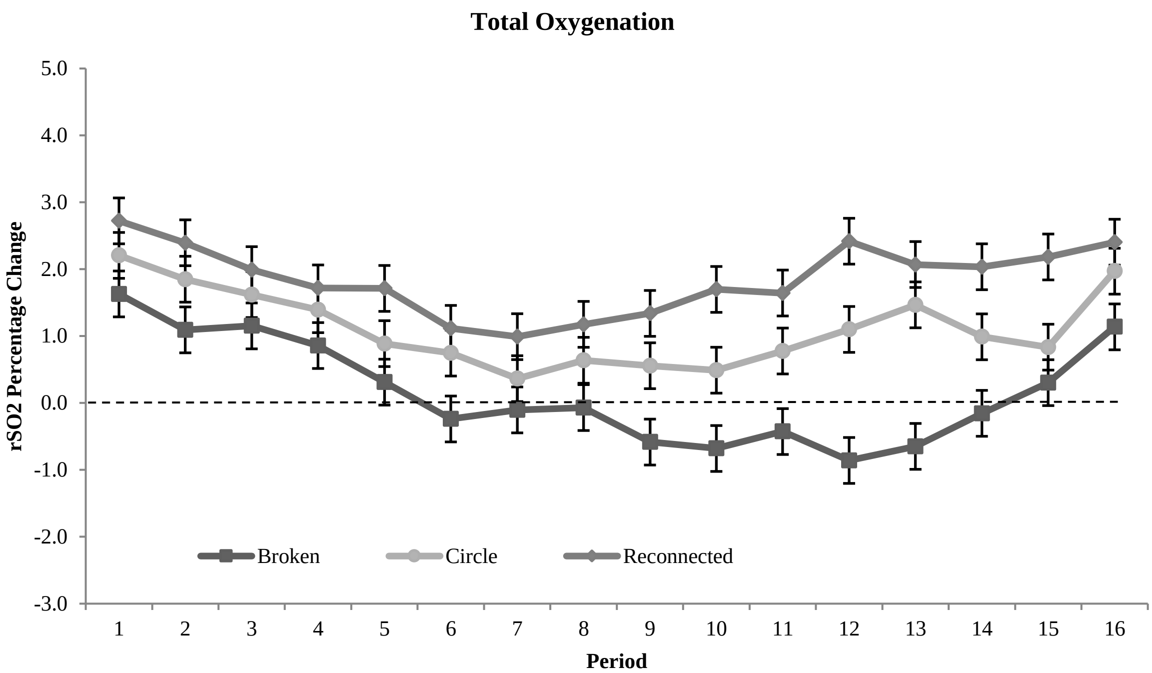


Figure 7. Mean percentage rSO2 change scores for total oxygenation in each condition over 16 periods of watch. The dashed line represents a change score of 0, or zero change. Error bars depict standard error.

There was a significant hemisphere difference, $F(1, 42) = 4.85$, p = .033, $\eta_p{}^2 = .104$, with the right hemisphere (total mean = 1.324) showing higher levels of oxygenation compared to the left hemisphere (total mean = 0.769). This is shown in Figure 8.

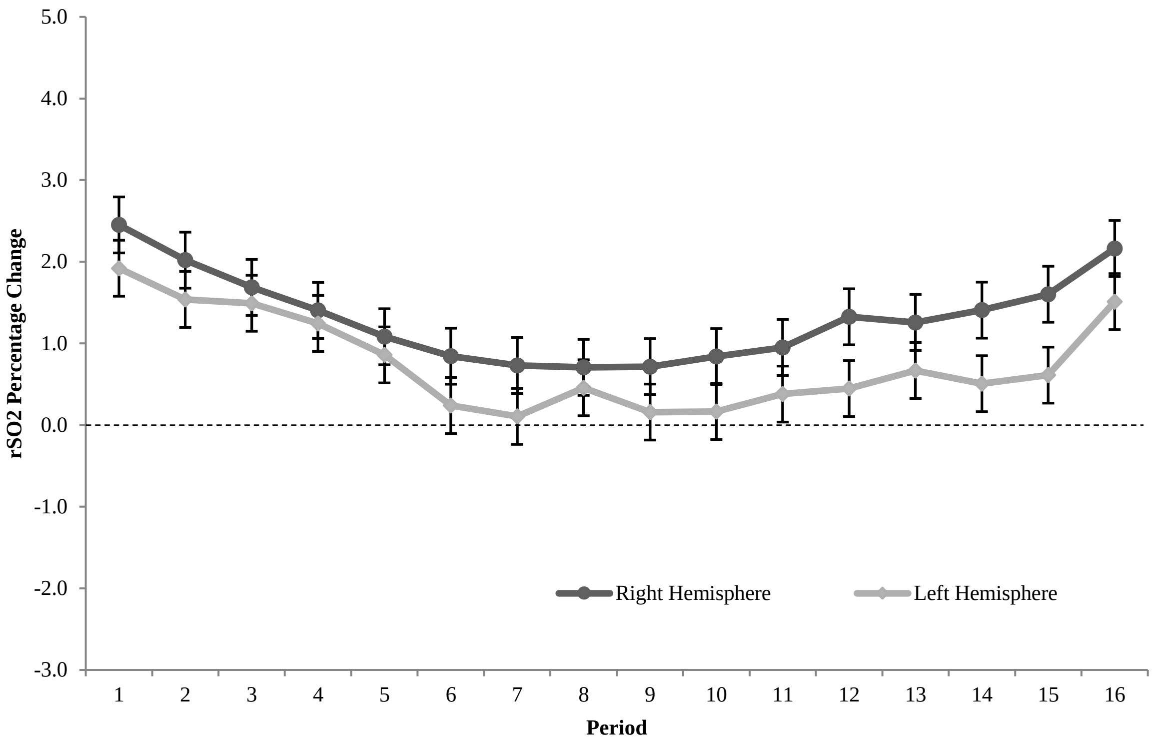
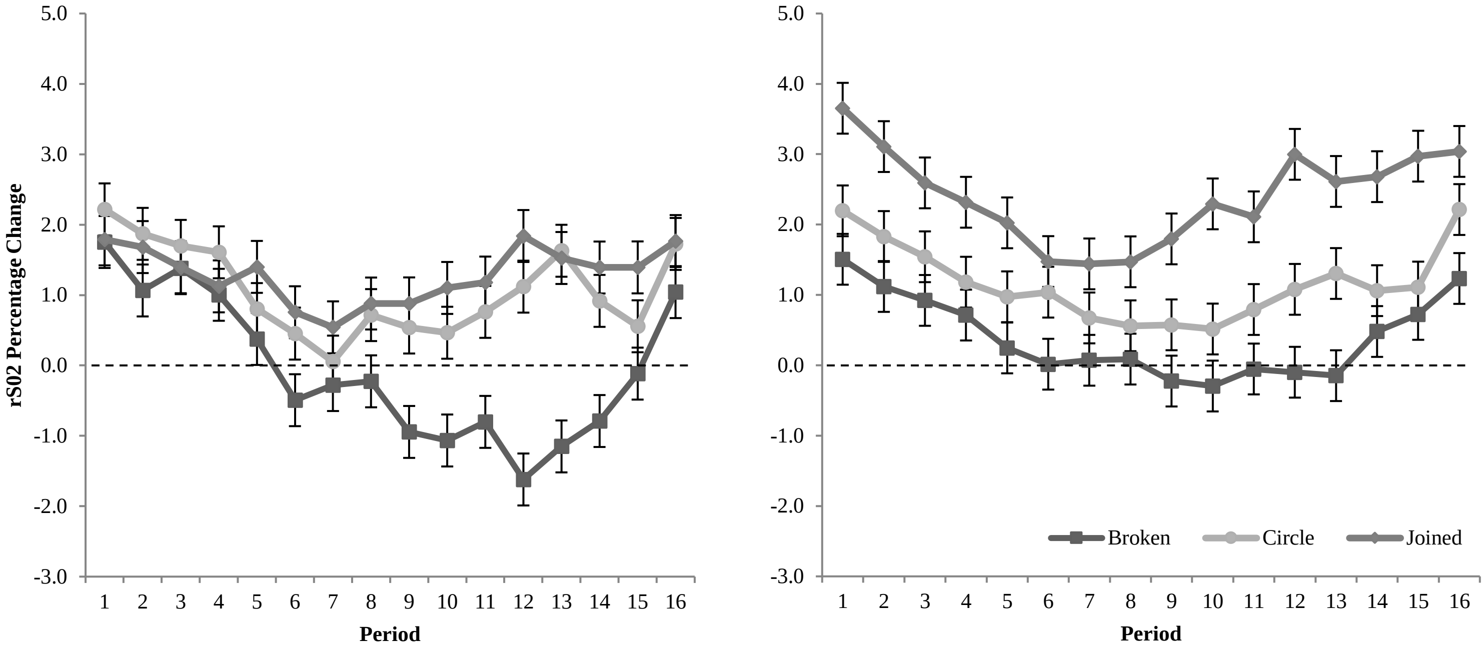


Figure 8. Mean percentage rSO2 change scores for total oxygenation of each hemisphere over 16 periods of watch. The dashed line represents a change score of 0, or zero change. Error bars depict standard error.

There was a significant period by hemisphere by group 3-way interaction, $F(30, 630) = 1.52$, p = .038, $\eta_p^2 = .068$. This appears to be a result of a deviant left hemisphere trend in the broken condition. Right hemisphere oxygenation reveals a similar trend across all groups. To further examine this 3-way interaction, each hemisphere was individually examined with a 3 (shape: circle, broken, and reconnected) by 16 (period of watch) repeated-measures ANOVA. For the right hemisphere, there was no significant main effect for group, $F(2, 42) = 2.65$, p = .083, $\eta_p^2 = .112$. There was a significant quadratic trend for period of watch, $F(1, 42) = 31.29$, p = .000, $\eta_p^2 = .427$. A decrease in rSO2 was observed over the first half of the vigil, before an increase in rSO2 occurred in the final half. There were no significant period by group linear trends, $F(2, 42) = .28$, p = .762, $\eta_p^2 = .013$, or quadratic trends, $F(2, 42) = .05$, p = .951, $\eta_p^2\eta_p^2 = .002$. The right hemisphere rSO2 percentage change scores are presented in Figure 9 (right side).

For the left hemisphere, there was no significant main effect for group $F(2, 42) = 1.27$, $p = .291$, $\eta_p^2 = .057$. There was, however, a significant linear trend, $F(1, 42) = 7.63$, $p = .008$, $\eta_p^2 = .154$, and a significant quadratic trend, $F(1, 42) = 20.29$, $p = .000$, $\eta_p^2 = .326$. There was also a significant period by group linear trend interaction, $F(2, 42) = 4.34$, $p = .019$, $\eta_p^2 = .171$. The circle and reconnected conditions show a similar trend to that of the right hemisphere, with a decrease in rSO2 observed over the first half of the vigil, before an increase in rSO2 occurs in the final half. For the broken condition however, the initial decrease in rSO2 continues for a longer time into the latter periods of the vigil compared to the circle and reconnected groups. The left hemisphere rSO2 percentage change scores are presented in Figure 9 (left side).



Left Hemisphere

Right Hemisphere

Figure 9. Mean percentage rSO2 change scores for the left hemisphere and right hemisphere for each group over 16 periods of watch. The dashed line represents a change score of 0, or zero change. Error bars depict standard error

Correlation between performance measures and oxygenation

In addition to the trend analysis, both between-subjects and within-subjects correlations between performance measures and hemisphere activation were examined. To calculate within-subject correlations, we used a technique described in Head and Helton (2014) and Zelenski and Larsen (2000). For each individual participant, their performance and physiological metrics for each of the 16 periods were converted to standardized within-subjects z-scores using Fisher's Z transformation. These z-scores were then combined or "chained" (also see Helton, Funke, & Knott, 2014; Wilson, 2015) and used to calculate within subjects correlations. To control for familywise error rate the Holm-Bonferroni procedure was used. This procedure is more powerful than the Bonferroni procedure yet maintains the Type I error rate (Park et al., 2009). Both the between-subjects and within-subjects corrected correlations are presented in Table 1 below.

Table 1. Correlations between variables (within-subjects below main diagonal; between-subjects above main diagonal).

	RH	LH	Hits	False Alarms	RT	A'
Right Hemisphere		**.768****	.019	.116	.153	-.001
Left Hemisphere	**.728****		.165	-.132	.106	.184
Hits	.004	.076		-.241	**-.538****	**.981****
False Alarms	.073	-.039	.018		-.066	**-.420****
RT	.060	.025	**-.183****	-.058		**-.485****
A'	-.010	.083	**.969****	**-.216****	**-.158****	

** *Significant after Holm-Bonferroni correction*.

No significant correlations between hemisphere and performance were found in the between-subjects data. Initially for the within-subjects data there were significant correlations between left hemisphere activation and both hits and *A'* scores, as well as a significant correlation between right hemisphere activation and false alarms. Following correction, however, these were not significant.

Questionnaire

The self-report stress scale items were combined to form three factors of; distress, task engagement, and mind wandering. The change scores of these three factors were then examined with a series of one-way ANOVAs to assess group differences. There were no significant differences between groups for either distress, $F(2, 44) = .10$, p = .909, $\eta_p^2 = .005$, or mind wandering, $F(2, 44) = 1.34$, p = .272, $\eta_p^2 = .060$. There was a significant difference between groups for task engagement, $F(2, 44) = 4.71$, p = .014, $\eta_p^2 = .183$. A paired comparison for each of the change scores was performed. Task engagement and mind wandering showed no significant differences, while distress did show a significant difference, $t(44) = -10.27$, p = .00, with higher scores being found in the post-task questionnaire. Mean questionnaire scores for each group are shown in Figure 10.

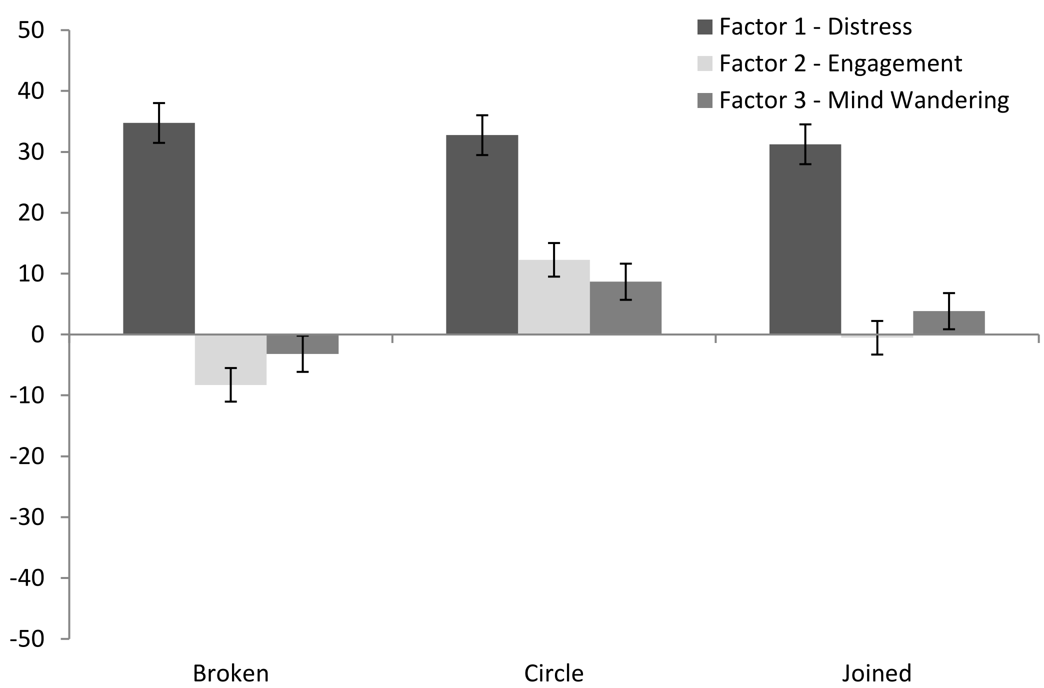


Figure 10. Mean questionnaire change scores for each factor for each group. Error bars depict standard error.

Discussion

It was hypothesized that the reconnected and circle conditions would show similar patterns of accuracy over time, as well as no significant differences in level of accuracy between each other. It was also hypothesized that these two conditions would show a higher level of performance compared to the broken condition. Both of these hypothesized results were found in the current experiment, as evidenced by hit rate and A' trends over time. It was also hypothesized that none of the conditions would show a significant vigilance decrement (although it was hypothesized that there would be overall differences). Consistent with the decrement hypothesis, no statistically significant decline in performance over periods of watch was detected. The group differences in accuracy, as well as the observed patterns over time, are extremely similar to those found in de Joux et al. (2015b). In previous research, it was suggested that the lack of a significant decrement may be due to this task being too difficult to perform, which means that performance is representing somewhat of a floor effect. This is somewhat difficult to support though, given that hit rates are at an acceptable level initially. An alternative explanation to the floor effect suggestion is that, due to the tasks themselves were more complex and therefore were less challenging for participants to maintain self-regulation and focus on the task. While task difficulty accentuates the vigilance decrement (See, Howe, Warm & Dember, 1995), the increased complexity of the shapes here may not necessarily mean that they are more difficult to attend to. Rather, more complex objects makes the task of sustaining attention easier to perform over time (Langner et al., 2010), hence a lack of significant decrement. The lack of differences between the circle and reconnected conditions, as well as the differences between these two conditions compared to the broken condition, supports the configural superiority effect in which objects that form a whole are processed more efficiently than those which do not (Pomerantz, Sager & Stoever, 1977;

Pomerantz & Kubovy, 1986; Pomerantz & Pristach, 1989). The broken shape, having no discernible global aspect, made it more difficult for participants to allocate attention to the target locations, thus the lower accuracy. As stated, these results were hypothesized to occur.

For reaction time there were significant differences between the groups, with the circle group showing the quickest reaction times, followed by the reconnected condition, and the broken condition showing the slowest responses. There were no hypotheses pertaining to reaction time data, due to no observed reaction time differences between the three groups in previous studies (de Joux et al., 2015b). However, in the current experiment a significant quadratic trend over periods of watch was found in which reaction times increased during the first half of the vigil before levelling off in the final periods. The group differences in reaction time may, however, provide additional support to the configural superiority hypothesis presented earlier. One possible cause of the reaction time differences between the circle and reconnected conditions is the spatial extension of the reconnected shape compared to the circle shape. The extended spatial information provides more information that is required to be processed before a decision is to be made. While the configural superiority effect influences performance in regards to target detection, this may come at the expense of speed for reconnected shapes. The finding of significant reaction time differences in the current experiment, as opposed to that of de Joux et al. (2015b), could possibly be attributed to the extended vigil length allowing more time for differences to become apparent, as well as greater power for the statistical tests.

The rSO2 percentage change scores were characterised by a number of trends. First, there was a significant hemisphere difference, with the right hemisphere showing higher levels of activation compared to the left hemisphere overall. This finding was hypothesized, as regardless of trend differences over time, the right hemisphere is typically found to be more activated during vigilance tasks (Parasuraman, Warm & See, 1998; Shaw et al., 2009; Stroobant & Vingerhoets, 2000; Warm, Matthews & Parasuraman, 2009).

Second, total oxygenation showed a significant quadratic trend, with rSO2 initially decreasing before increasing in the latter periods of watch. An initial increase in oxygenation is common when engaging in demanding tasks and an eventual decrease in oxygenation is not unexpected in a vigilance task (Bogler, Mehnert, Steinbrink & Haynes, 2014; de Joux et al., 2015a; de Joux et al., 2013; Derosière, Mandrick, Dray, Ward & Perrey, 2013; Hancock, 2015; Jeroski, Miller, Langhals & Tripp, 2014; Shaw et al., 2013). Researchers have noted that many vigilance tasks are often characterized by an early stage of passive perceptual learning (Ong, Russell, & Helton, 2013; Head & Helton, 2015). In this initial stage, frontal activation should be elevated and then activity should decline with experience with the task. Later during the task, activation may increase again as sustained attention demands increase resulting in recruitment of more neural resources. While passive perceptual learning does not seem to be greatly influencing trends from a performance standpoint, this trend in the physiological data may be indicative of some form of neural correlate to perceptual learning processes. Researchers have suggested, when using similar tasks, that declines in rSO2 over time may result from a decrease in blood flow supply to those neural areas. This phenomenon can occur when total available resources are near maximum capacity levels; or when less cognitive function is required (Jeroski et al., 2014; Satterfield, Shaw & Finomore, 2014). An increase in cerebral oxygenation is in turn seen as the result of an increase in blood flow to these areas, a phenomenon that occurs when these areas are unable to match the required resource level. The trends observed of cerebral activation found in the current experiments could be interpreted as participants responding to the initial demands of the task by an increase in cerebral activation from resting baseline. Resource theorists have also proposed that after a decrement in performance vigilance tasks often result in participants' performance oscillating around a lower level of performance, a point in which the cognitive resource demands of the task are matched by the replenishment rate of those resources (Humphreys & Revelle, 1984; Parasuraman & Giambra, 1991). While this may not be strictly true in this case, as there is no performance decrement, this could partially explain the relatively stable level of task performance found in all three conditions, as well as the stable accuracy found in de Joux et al. (2015b). It may be that the resource demands for the task requirements are met near immediately. The increase in oxygenation in the second half of the vigil may represent an attempt to maintain this level of performance as the sustained attention demands increase. In other words, the quadratic trend may represent a dynamic process in which an appropriate level of neural activity and neural resource recruitment and replenishment is sought to enable stabile levels of performance.

A third notable trend is the bilateral activation observed in the circle and reconnected conditions. It is possible to attribute the observed bilateral activation to task difficulty demands in the task, a similar observation made by Helton et al. (2010) using fNIRS and Satterfield, Shaw and Finomore (2014) in a task measuring cerebral blood flow velocity. Subjective measures of distress appear to support this, as results indicate an increase in task distress from baseline levels, suggesting the task was stressful. Some of the results found in the current experiment may not, however, quite fit with this explanation of task difficulty being the main cause of bilateral activation found here. Particularly, a period of watch by hemisphere by group interaction was observed, with a significant hemisphere by period effect being found in the broken condition, indicating hemisphere differences over time (i.e., increased right hemisphere activation compared to the left hemisphere). This is despite the broken condition being the most difficult of the three conditions by traditional objective measures of performance (lowest hit rate, lowest A’ score, longest reaction time). In contrast, the circle and reconnected conditions, which were the least difficult conditions by objective measures (high hit rates, high A’ scores, quicker reaction time), showed bilateral activation and greater total activation overall. The task difficulty explanation should mean increased bilateral activation in the broken groups, and less in the reconnected and circle groups. Alternatively, the differences in hemisphere trends for the broken condition could be explained as a result of the requirement to recruit additional local processing resources above and beyond those of which are activated due to task difficulty, as well as increased expertise at processing local information. It is established that a decrease in blood flow is observed with expertise or practice (Anderson, 2000; Shaw, Satterfield, Ramirez & Finomore, 2013). The decrease in blood flow in the left hemisphere in the broken condition may be due to the separate objects being processed as separate global features which require integration, instead of as local objects of a global whole. The broken condition shows similar patterns to the circle and reconnected conditions in the initial phases of the task, and overall displays the same quadratic trend observed in these conditions (albeit not a significant one), however it is the final periods of the vigil in which the lateralization trend is observed. The right hemisphere in the broken condition does show a similar pattern to those found in the other groups; however the left hemisphere continues to show a decrease for a more extended period of time. This extended decrease over time may be due to the left hemisphere becoming more specialized at processing local information over time, thus requiring less resource demand to perform the processing. The hemisphere trends in the circle and reconnected groups may then be explained by the requirement to engage in near equal amounts of local and global feature processing. The local-global processing requirements explanation provides a better explain to the differences found in the current results compared to the solely task- difficulty explanation.

The activation trend differences between the circle/reconnected conditions and the broken condition provides support to the suggestion that non-typical laterality profiles found in previous research using similar stimuli are influenced by local-global processing requirements; evoked by the configural properties of the stimuli used (Funke et al., 2010; Funke et al., 2012; Jeroski et al., 2014; Nelson et al., 2014; Shaw et al., 2013). This is further illustrated by the within-subjects and between-subjects correlation analysis (Table 1), which do not show large correlations between cerebral activation and performance metrics. This suggests that the hemisphere differences and trends found here may be less linked to performance and more linked to the perceptual demands of the task itself. The circle and reconnected shapes, both of which form configurative wholes, exhibit more bilateral activation. In contrast the broken shape, which does not form a configurative whole, exhibits increased right hemisphere activation compared to the left hemisphere in the latter periods of the vigil. Although bilateral activation is a function of task difficulty (Helton et al., 2010), the laterality profiles found here cannot be solely attributed to task difficulty demands, due to these patterns of activation being found in the better performing conditions. It is also proposed that the differences in activation over time found in this experiment may explain performance differences found in previous experiments using these stimuli. This suggests that the differences found in previous experiments using similar stimuli are predominantly due to local-global feature discrimination rather than associated difficulty. It should be noted that these trends may not necessarily be generalizable to all vigilance tasks. Rather, they may only be generalizable to vigilance tasks in which an elevated level of local-global feature discrimination or processing is required. An additional suggestion for future research is in regards to the measurement device utilized here. Other hemodynamic measurements, such as TCD, offer alternative views on blood flow and cerebral activity. Indeed, many studies advocate for the use of both TCD and fNIRS in order to more fully capture cerebral hemodynamic patterns (Steiner et al., 2009). Furthermore, Funke et al., (2010) used both TCD and fNIRS to show that these separate measures of cerebral activity are not as closely linked as once assumed during vigilance tasks. The utilization of TCD during a task such as this may allow for the further testing of whether the trends found here are related to perceptual processing requirements rather than workload demands.

These findings may be of use to authors who are investigating hemodynamic activity during vigilance tasks and do not find typical laterality profiles, given that certain stimuli may evoke the need for processing of local-global objects. These findings may also be of use to authors who are seeking to use more complex or novel stimuli in vigilance tasks, as local-global processing requirements may cause significant effects via influencing bilateral activation trends over time.

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