Resting Heart Rate Variability in Young Women is a Predictor of

EEG Reactions to Linguistic Ambiguity in Sentences

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Abstract

Recent research has found a relationship between heart rate variability (HRV) and cognitive control mechanisms underlying various experimental tasks. This study explored the interaction between gender and resting-state HRV in brain oscillatory activity during visual recognition of linguistic ambiguity while taking state and trait anxiety scores into account. It is well known that stress or anxiety increases arousal levels, particularly under uncertainty situations. We tasked 50 young Mandarin speakers (26 women; average age 26.00 ± 4.449) with the recognition of linguistic ambiguity in English (foreign) sentences with the purpose of imposing a sense of uncertainty in decision-making. Our results revealed a dependency between resting-state HRV and theta/alpha power in individual women. Low HRV women showed stronger theta/alpha desynchronization compared with their high HRV counterparts, independent of topographic localization. However, low and high HRV men exhibited comparable theta/alpha activity. Trait anxiety scores affected alpha power in the parieto-occipital regions, whereas men with higher scores and women with lower scores showed stronger alpha desynchronization. We posit that stress-provoking situations may impose additional effects on theta/alpha desynchronization in the frontal and temporal regions, a condition in which the interdependency between brain oscillatory activity and resting-state HRV could interact with cognitive control differently in men and women.

Key words: Anxiety, event-related spectral perturbations (ERSPs); resting-state HRV; semantic recognition; stress; uncertainty in decision-making.

1. Introduction

Heart rate variability (HRV) is defined as variation in successive inter-beat intervals in the time series of electrocardiograms (ECGs), and is considered a physiological index for monitoring parasympathetic influence on cardiac function (Cardiology, 1996; Luque-Casado et al., 2013; Murray and Russoniello, 2012). Recent research has reported an association between HRV and cognitive control in various experimental tasks. Cognitive control[1] refers to the regulatory processes responsible for action planning, developing expectancy, response inhibition, and error detection (Luft et al., 2009). High resting-state HRV is accompanied by enhanced cognitive control over tasks that require working memory, voluntary attention, and inhibitory control (Hansen et al., 2004; Hovland et al., 2012; Park et al., 2013). Conversely, mental workload is negatively correlated with task HRV (Mukherjee et al., 2011). Studies on HRV have also considered differential gender effects of parasympathetic (or vagal) control on behavioral performance and on functional brain networks (Antelmi et al., 2004; Young and Benton, 2015). Nonetheless, the intricate relationships among brain oscillations, resting-state HRV, gender, and psychological traits in cognitive control tasks have yet to be fully elucidated. This study helps bridge this research gap by empirically evaluating the relationship between resting-state HRV and EEG reactions as participants perform a task involving visual recognition of linguistic ambiguity in English sentences. This task imposes a strong sense of uncertainty in decision-making. It is known that stress or anxiety increases arousal levels particularly under uncertainty situations (Cavanagh and Shackman, 2015; Gray, 2000). A novelty of this study lies in our delineation of distinct EEG oscillatory patterns between high and low HRV young women as compared with men by controlling for anxiety effects.

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[1] The terms "cognitive control" and "executive control" are used interchangeably in this study, but the former also considers the executive control triggered by monitoring processes in decision-making under changeable external conditions

Uncertainty refers to a situation in which existing knowledge and rules are insufficient for predicting future events within a given environment (Pourtois and Krebs, 2011). It is associated with enhanced monitoring behaviors and increased voluntary attention to decision outcomes (Osman, 2010). The default reaction to uncertainty is widely accepted as the sympathoexcitatory preparation for the fight-or-flight response, which has been hypothesized to be related to the well-known tendency of prioritizing negative information over positive information (the so-called negativity bias) (LeDoux, 1998; Thayer et al., 2012). High resting-state HRV is associated with less negativity bias and a greater willingness to approach positive and novel objects (Shook et al., 2007). Researchers have shown that the amygdala responds rapidly to positive and negative stimuli (e.g., emotional faces), but may subsequently be inhibited by the prefrontal cortex (PFC) if the stimuli are appraised as safe. Under uncertainty, the amygdala and PFC become hypoactive that manifests as a disinhibition of sympathoexcitatory circuits and a reduction in task-related HRV. Uncertainty in decision-making has important links to emotion and anxiety disorders (Yoshida and Ishii, 2006). For instance, highly anxious participants tend to perceive ambiguous situations as more emotionally negative (Maoz et al., 2016; Qiao-Tasserit et al., 2017). Anxiety refers to a degree of mental tension induced by stressful experiences, predicted future dangers, or anticipated failures. State-anxiety is defined as unpleasant emotional arousal when confronting dangerous or threatening situations. Previous studies on lexical decision reported that participants who experienced pronounced state-anxiety were inclined to recognize ambiguous information as more threatening (Blanchette and Richards, 2003; Davey et al., 2006). Trait-anxiety, on the other hand, refers to a stable attribute in healthy individuals that is less dependent on specific situations; it is related to increased arousal levels in the behavioral inhibition system (BIS) which, as noted, is particularly pronounced under uncertainty situations. In other words, trait anxiety can impact cognitive assessment, resulting in overestimates of the likelihood of negative outcomes in ambiguous situations (Gray, 2000).

Acts of reading and recognition of written sentences require all mental components related to cognitive control, including attentional processing, memory regulation, and decision making.

Theta (4-8Hz) oscillatory activity reveals a neurophysiological mechanism for optimally adapting behaviors to environmental uncertainty, that is, situations which elicit anxiety and demand cognitive control (Cavanagh and Shackman, 2015). A deficit in theta oscillations is associated with disorders related to inhibitory control, such as alcohol dependency (Kamarajan et al., 2015). Lower-alpha oscillations (8-10Hz) reflect the degree of voluntary attention during decision-making in a variety of sensory, cognitive, or motor tasks. Upper-alpha oscillations (10-12Hz) indicate the involvement of semantic long-term memory in cognitive processing (Klimesch, 1999). Upper-alpha oscillations also play a role in top-down inhibitory control over short- and long-latency stress reactivity of blood pressure in the defensive cardiac reflex (Aftanas et al., 2015). In general, alpha oscillations indicate the degree of readiness to perceive external stimuli and to execute active motions (Klimesch et al., 2007). The amplitude of stimulus-induced alpha-desynchronization has been used to index arousal levels during task-execution. Recent studies have examined the association between alpha activity and HRV parameters in a variety of cognitive tasks (Dzhebrailova et al., 2015), under resting-state conditions (Capotosto et al., 2014), and during the sleep-wake cycle (Martin et al., 2015), while also taking anxiety effects into account (Levine et al., 2016). However, those studies have yielded inconsistent, and at times contradictory, findings on alpha activity.

Physiological responses to stress can be classified into two phases (Lucassen et al., 2014). First, the fight-or-flight response involves rapid activation of the autonomic nervous system (ANS), accompanied by a release of hormones for quickly elevating basal metabolic rate, blood pressure, and respiration to prioritize blood flow to vital organs, such as the heart and skeletal muscles. Second, the hypothalamus-pituitary-adrenal (HPA) axis is activated followed by directed attention diverted to the most urgent and important elements in the stressors while other less urgent functions are temporarily suppressed (Joëls et al., 2012). A meta-analysis of neuroimaging studies on task HRV suggested that HRV may indicate the degree to which a system guided by the medial PFC is integrated into the brainstem nuclei for the direct regulation of the heart, and that it may potentially be used as a marker to indicate levels of stress and/or

health (Thayer et al., 2012). A study employed neuroimaging and positron emission tomography (PET) identified decreased activity in the limbic system when the brain reacted to a stressful arithmetic task. Specific reactions included deactivation of the hippocampus, amygdala, insula, hypothalamus, ventral striatum, medial PFC, and anterior cingulate cortex (Pruessner et al., 2008). The hippocampus deactivation was also linked to the amount of cortisol release, suggesting a linear relationship between hippocampal deactivation and activity in the HPA axis. Stress and the perception of threats can cause anxiety and induce cardiac vagal withdrawal. Indeed, many HRV parameters have consistently indicated low vagal and elevated sympathetic activity in anxiety-provoking situations (Friedman, 2007). Many studies have further identified a negative relationship between cardiac vagal control and trait anxiety (Friedman, 2007; Virtanen et al., 2003). Balanced HRV presents relatively equal power across high frequency (HF; 0.15-0.4Hz) and low frequency (LF; 0.04-0.15Hz) parameters in ECG time series. However, an increase in arousal levels is reflected by a decrease in HRV, suggesting an overall shift from autonomic balance toward increased sympathetic activity characterized by higher power in the LF band and less variable heart rates. HF power has been adopted as an HRV index to characterize a variety of anxiety disorders, including panic, post-traumatic stress, generalized anxiety, and obsessive compulsive disorders (Krypotos et al., 2011). One recent meta-analysis confirmed the hypothesis that anxiety disorders are generally associated with a reduction in HRV (Chalmers et al., 2014).

Previous research has also consistently provided evidence on a gender difference in physiological responses to stress (Kogler et al., 2016; Tomova et al., 2014). For example, Kurina et al. (2004) identified an inverse relationship between perceived stress at work and average cortisol levels in women, but not in men. It was hypothesized that women are more likely to engage in nurturing and network-building activities in responding to stress in order to promote safety and thereby to reduce stress levels. Resting-state alpha activity has also been independently studied for gender effects (Biswal et al., 2010); however, related results have been largely inconclusive. One study found no gender difference in alpha activity; other studies reported stronger alpha power in men than in women; and still other studies reported stronger

alpha power in women than in men (Aurlien et al., 2004; Nikulin and Brismar, 2005; Zappasodi et al., 2006). One study using individually determined peak alpha frequencies reported that a significant gender difference is pronounced in the parieto-occipital regions in the lower- and upper-alpha bands and that women present stronger alpha power than men. Similar results were observed in higher frequency bands, such as beta and gamma waves (Jaušovec and Jaušovec, 2010). Several studies on healthy participants have also shown that women exhibit stronger alpha and beta power compared with men (Brière et al., 2003; Marceglia et al., 2006; Nikulin and Brismar, 2006). Furthermore, in psychological testing, the anxiety scores of women tend to be higher than those of men (Egloff and Schmukle, 2004). Nonetheless, these differences are strongly dependent on the social norms of the communities in which individual live. Several time- and frequency-domain HRV parameters also differ according to gender. For instance, the HF parameter is higher in women than in men, whereas the LF parameter is higher in men than in women (Antelmi et al., 2004).

In summary, cognitive control tasks involving uncertainty in decision-making tend to induce high levels of stress or anxiety, which activates the BIS and reduces task HRV. Men and women differ in physiology (hormonal status and HRV) and social constructs; they may show different interactions between anxiety and the BIS. As such, we tasked 50 young Mandarin speakers (26 women; average age 26.00 ± 4.449) to visually recognizing linguistic ambiguity in English (a foreign language) sentences. Because there were no explicit rules for making a correct decision, the language task was relatively difficult for our participants who achieved an accuracy rate of 50-80% (Roos et al., 2017). Resting-state ECGs were recorded for 8 min before the task with 4 min eyes-closed followed by 4 min eyes-open conditions. The State-Trait Anxiety Inventory (STAI) (Spielberger, 1983) was also administered to all participants. Because theta and alpha oscillations are highly relevant to cognitive control and language comprehension (Kawasaki et al., 2010; Röhm et al., 2001), our analysis focused on the interactions between brain oscillatory activity and gender in the two frequency bands, while adopting HRV and anxiety scores as control variables in repeated measure ANOVA. HRV decreases significantly with age

until the fourth decade of life with the steepest decrease in the third decade (Antelmi et al., 2004). Thus, all women recruited for the EEG experiment were in their 20s. We recruited men in their 20s and 30s based on our hypothesis that the association between resting-state HRV and cognitive control would be stronger in young women than in men when they solve a stressful task that imposes a strong sense of uncertainty in decision-making.

2. Results

2.1 Behavior data

Cronbach's alpha values for the cSTAI-State and -Trait scores were 0.896 and 0.867, respectively, and both of these values were significant at $p < .001$ (test size $\alpha = 0.05$). Ten men and fifteen women were classified within the High-HRV group, and the remaining participants were assigned to the Low-HRV group, wherein classification was made according to the median split of the adjusted SDNN (jSDNN) indices (See the definition in the Experimental Procedures section). Table 1 lists the reaction times (RTs) and response accuracy rates for the English language task as well as the mean scores of state and trait anxiety in each group. Compared with the 24 men, the 26 women practiced the task more on average before the EEG experiment. Note that the High-HRV participants (both men and women) had shorter RTs on this task than did their Low-HRV counterparts across various types of sentences. However, the jSDNN index was only significantly correlated with RT in women. Women also presented stronger correlations between jSDNN and response accuracy. HF power provided similar correlations to those listed in Table 1; however, the 24 men presented a stronger relationship between trait anxiety scores and HF power (-.348). Finally, although the anxiety scores of women were also higher than those of men, the group difference was insignificant.

Table 1 about here.

Table 2 lists the average and standard deviation values of HRV parameters for the various groups and also reveals how strongly each of these parameters correlates with anxiety scores

(See the definition of HRV parameters in the Experimental Procedures section). After controlling for anxiety scores, univariate testing revealed significant differences between Low- and High-HRV groups during the 8 min monitoring period for rMSSD ($F_{1,46}$ = 37.546, p < .001), HF power ($F_{1,46}$ = 15.745, p < .001), NN50 ($F_{1,46}$ = 6.985, p = .011), and pNN50 ($F_{1,46}$ = 6.160, p = .017). These parameters also exhibited significant differences between genders for rMSSD ($F_{1,46}$ = 4.809, p = .033), NN50 ($F_{1,46}$ = 4.719, p =.035), and pNN50 ($F_{1,46}$ = 4.528, p = .039), which are consistent with those of Antelmi et al. (2004). Women presented higher rMSSD, NN50, and pNN50 values than did men, and their higher average values were mainly contributed by individuals in the High-HRV group. The normalized frequency-domain parameters only showed gender effects under the eyes-closed condition whereby for Nu LF ($F_{1,46}$ = 5.734, p = .021), Nu. HF ($F_{1,46}$ = 5.683, p = .021), and LF/HF ratio ($F_{1,46}$ = 6.996, p = .011). Under the eyes-open condition, none of these normalized parameters showed any significant gender or HRV-group effects.

As shown in Table 2, the relative magnitudes for the normalized parameters across HRV groups under eyes-open conditions were consistent with those for time-domain parameters (monitored for 8 minutes) and HF power (also monitored for 8 minutes). Notably, those normalized parameters under eyes-closed conditions showed opposite results. In summary, the jSDNN index preserved original features reasonably well under different HRV parameters. The values of HF and jSDNN were less dependent on gender and mean heart rate (HR) than other parameters and were also robust to eyes-closed and eyes-open conditions (See the Experimental Procedures section). ANOVA results were compared by using either jSDNN or HF as a control variable in the prediction of theta/alpha oscillatory activity.

Table 2 about here.

2.2 Time-frequency analysis

Figures 1 and 2 present ERP and ERSP plots in the 11 scalp regions for the 50 participants recruited in the English language task. We only observed minor differences between the ERPs of

ambiguous and unambiguous sentences in the frontal regions; there was no visible difference in ERSP between the two types of sentences. As suggested by the behavioral data in Table 1, the two types of sentences may have interactions with gender and HRV. For simplicity, the results reported in this section are a composite of results obtained for the two types of sentences. Because the participants were instructed to identify sentences with semantic ambiguity, the N400 component was more pronounced in the frontal, temporal, and parieto-occipital regions. The recognition of written sentences is known to engage language as well as non-language processes. Non-language processes are those involved in the recognition of visual stimuli, whereas language processes are involved in the phonological, syntactic, and semantic recognition of sentences. As shown in Figure 1, the early P100 and N170 components during the 100−200ms interval were well pronounced in the parieto-occipital regions, and were likely associated with the physical properties of sentences, such as the form and size of letters. In speech recognition, phonological structure is considered a physical property (Dujardin et al., 2011), and the N170 component has been associated with phonological awareness and grapheme-phoneme conversion (Maurer and McCandliss, 2008; Sacchi and Laszlo, 2016). Both brain hemispheres are known to be engaged when solving complicated language tasks (Horowitz-Kraus et al., 2014; Riès et al., 2016). In Figure 1, the N400 and P600 components were respectively related to the semantic and syntactic recognition of sentences, and were pronounced in both the left and right scalp regions. Overall, the ERP patterns in the figure show strong agreement with those reported in the previous literature (Qi et al., 2016; Tsai et al., 2013).

As shown in Figures 2(A) and 2(B), low-frequency (i.e., delta and theta) synchronization was pronounced in the parieto-occipital regions, which may be associated with visual words, working memory processes, and selective attention (Başar, 2012a; Knyazev, 2007). In the later stage following the sentence onset, we observed strong theta and low alpha desynchronization in all scalp regions, which could be related to voluntary attention. High frequency desynchronization (i.e., the alpha and beta range) was also pronounced in the parieto-occipital regions. State anxiety was not shown to have a significant effect on ERSPs; therefore, we removed this variable from

further analysis. The ANOVA results reported in subsequent sections focus on interactions between HRV and gender in terms of theta and alpha oscillations by controlling for trait anxiety scores.

Figures 1 and 2 about here.

2.2.1 Theta activity (4-8Hz)

Table 3 shows the results of repeated measures ANOVA. The region-by-gender-by-jSDNN effect was significant in the theta range during the 100−300ms post-onset interval when gender, jSDNN, and cSTAI-Trait were simultaneously used as control variables. On average, the gender-by-jSDNN effect was also significant. To help interpret these results, Figure 3(A) plots the power of theta oscillatory activity in different scalp regions during the 100−300ms post-onset interval for the four groups, classified according to gender and jSDNN. Women in the Low-HRV group showed strong theta desynchronization across all scalp regions; however, women in the High-HRV group exhibited strong theta synchronization compared with other participants, especially in the parieto-occipital regions. In addition, a discrepancy in theta power was observed among women in the two HRV groups across all scalp regions, and this discrepancy was more pronounced in the parieto-occipital regions. In other words, the region-by-gender-by-jSDNN effect was significant. Note that the ANOVA results and histograms in the figure only reflect the average theta power across participants. The partial correlation between jSDNN and theta power was .431 $\pm$ .125 on average during the 100−300ms interval by controlling for the effect of trait anxiety. The correlations in the left/right frontal, left/right temporal, and right central regions (.553 $\pm$ .027) were higher than those in other regions. Low-HRV men showed stronger theta synchronization in the parieto-occipital regions compared with High-HRV men. The average partial correlation was −.068 $\pm$ .115, with slightly stronger negative correlations in the parieto-occipital regions.

Table 3 and Figure 3 about here.

We observed a significant gender-by-jSDNN effect during the 300−600ms post-onset interval. As shown in Table 3, theta power was distributed differently in the 11 scalp regions. Figure 3(B) clearly illustrates that nearly all of the groups contributed to strong theta desynchronization across scalp regions on this task. Men in the two HRV groups did not show a significant difference in theta power across scalp regions. In contrast, theta desynchronization was stronger among Low-HRV women than among High-HRV women, resulting in a significant gender-by-jSDNN effect. The average partial correlations between theta power and jSDNN during the 300−600ms interval were $.545 \pm .073$ for women and $−.025 \pm .102$ for men. During the 600−900ms post-onset interval, the region and gender-by-jSDNN effects were also significant, resulting in theta power histograms similar to those shown in Figure 3(B). Specifically, the average partial correlations between theta power and jSDNN during the 600−900ms interval were $.393 \pm .107$ for women and $−.049 \pm .099$ for men. Note that the trait anxiety effect did not contribute significantly to theta power, a result which persisted even when jSDNN was excluded from repeated measures ANOVA.

2.2.2 Lower-alpha activity (8-10Hz)

The results of repeated measures ANOVA revealed significant regional and gender-by-jSDNN effects on lower-alpha desynchronization during the 100−300ms post-onset interval. Figure 4(A) presents histograms of lower-alpha desynchronization in different scalp regions in this interval. In women, the strength of lower-alpha desynchronization was primarily influenced by individuals in the Low-HRV group; that is, women in the High-HRV group made little contribution to lower-alpha desynchronization. The average partial correlation between jSDNN and lower-alpha power was $.446 \pm .093$ for women. Correlations in the parieto-occipital regions were also weaker than those in other scalp regions. In contrast, lower-alpha desynchronization was stronger among High-HRV men than it was among Low-HRV men, particularly in the parieto-occipital regions. The average partial correlation between jSDNN and lower-alpha power was $−.164 \pm .073$ for men. During the 300−600ms post-onset interval, the region-by-gender-by-trait and gender-by-jSDNN effects were both significant. Furthermore, for both men and women, the trait anxiety

effect was more pronounced in parieto-occipital regions than it was in other scalp regions. Men with higher trait anxiety scores showed stronger lower-alpha desynchronization than did men with lower trait anxiety scores; however, women with high and low trait scores showed the opposite result. The average partial correlations between jSDNN and lower-alpha power during the 300−600ms interval were .393 ± .078 for women and −.149 ±.055 for men.

Figure 4 about here.

The region-by-gender-by-trait effect showed a similar pattern during the 100−300ms interval as those during other intervals, but the estimated effect failed to reach statistical significance (p = .051) (See Table 3). As indicated in Figure 4(B), Low-HRV women exhibited stronger power in lower-alpha desynchronization compared with all other participants during the 300−600ms post-onset interval. Conversely, men in the two HRV groups exhibited a comparable pattern in lower-alpha desynchronization. During the 600−900ms post-onset interval, both the region-by-gender-by-trait effect and the gender-by-jSDNN effect were significant, which can be interpreted in the same way as the results during the 300−600ms interval. The average partial correlations between jSDNN and lower-alpha power were .333 ± .062 for women and −.131 ± .052 for men. Note that the region-by-gender-by-trait effect remained significant during the 300−900ms interval even when jSDNN was excluded from repeated measures ANOVA.

2.2.3. Upper-alpha activity (10-12Hz)

In this study, ANOVA results related to upper-alpha power were very similar to results related to lower-alpha power; that is, region-by-gender-by-trait and gender-by-jSDNN effects were found to be significant during the 100−900ms post-onset interval, wherein women with lower trait anxiety scores and men with higher trait anxiety scores generally showed stronger upper-alpha desynchronization in the parieto-occipital regions. Figure 5 presents histograms of upper-alpha desynchronization in different scalp regions during the 100−300ms and 300−600ms post-onset intervals. High-HRV women still presented weak upper-alpha synchronization in the frontal and central regions during the 100−300ms post-onset interval. Low-HRV women showed stronger

upper-alpha desynchronization in all regions, compared to other participants. The average partial correlations between jSDNN and upper-alpha power for women were as follows: .405 ± .075 (100−300ms), .385 ± .061 (300−600ms), and .301 ± .043 (600−900ms). The corresponding correlations for men were as follows: −.177 ± .078 (100−300ms), −.161 ± .037 (300−600ms), and −.137 ± .035 (600−900ms). The trait anxiety effect on upper-alpha power was independent of the jSDNN effect. In other words, ANOVA results for trait anxiety remained the same, even when jSDNN was excluded from analysis.

Figure 5 about here.

2.2.4 Summary

Behavioral data revealed that HRV can affect RTs in the English language task and that this effect tends to be more pronounced in women than in men. In the women group, the resting-state jSDNN index predicted the degree of arousal well during the recognition of linguistic ambiguity in sentences, and differentiated maximally among them in theta and alpha oscillations. Our ANOVA results revealed that the gender-by-jSDNN effect was significant during the 100−900ms post-onset interval within the three frequency ranges. Low-HRV women showed an exceptional power decrease in theta oscillations following the sentence onset and much stronger theta desynchronization during the 300−900ms interval compared with other participants. In contrast, High-HRV women presented stronger theta synchronization during the 100−300ms post-onset interval and weaker theta desynchronization during the 300−900ms interval. The jSDNN effect tended to be independent of topographic localization during the period critical for processing of semantic and syntactic information in sentences (i.e., The region-by-gender-by-jSDNN effect was insignificant during the 300−600ms interval). The partial correlations between jSDNN and theta power in women were significantly positive and generally higher in the frontal and temporal regions than in other regions. Theta synchronization was stronger for Low-HRV men than for High-HRV men in the parieto-occipital regions during the 100−300ms interval. Theta power showed greater consistency among men than among women during the 300-900ms

post-onset interval. In men, the partial correlations between jSDNN and theta power were negative and insignificant.

We obtained similar ANOVA results for lower- and upper-alpha oscillations. However, when the two alpha ranges were merged into a single range (8-12Hz), the effects of trait anxiety and jSDNN became less significant (i.e., higher p values) than those obtained in separate analyses. In women, the effect of jSDNN on alpha oscillations was independent of topographic localization during the 100−900ms post-onset interval, and the partial correlations between jSDNN and alpha power were significantly positive. Men in the two HRV groups presented similar alpha desynchronization patterns across scalp regions. However, the partial correlations between jSDNN and alpha power were negative and insignificant in men. The cSTAI-Trait scores revealed opposite effects on men and women; that is, women with relatively lower trait scores and men with relatively high trait scores showed a stronger power decrease in the parieto-occipital regions. There were 10 men and 15 women classified into the high anxiety group. During the 100−900ms post-onset interval, the discrepancy in alpha desynchronization between men with low and high trait scores was more pronounced among those in the High-HRV group, particularly in the parieto-occipital regions. In other words, alpha desynchronization in Low-HRV men was more consistent, regardless of trait anxiety scores. In contrast, we observed a pronounced discrepancy in alpha desynchronization between low and high anxiety women in the parieto-occipital regions during the 100−900ms interval. These results were independent of jSDNN; that is, women with lower anxiety scores presented a more pronounced power decrease in the parieto-occipital regions. Our results on trait anxiety among men are in good agreement with the previous findings by others (Knyazev et al., 2004; Savostyanov et al., 2009). Among women, however, our results suggest that other factors may also affect alpha desynchronization.

2.2.5 Remarks

As mentioned, HF power has been used as an HRV index for characterizing anxiety and stress-related disorders. When jSDNN was replaced by HF in repeated measures ANOVA, then the region-by-gender-by-trait effects in the lower- and upper-alpha ranges were less pronounced

(with p-values ranging from .002 to .090). In contrast, gender-by-HF or region-by-gender-by-HF interactions were insignificant across all frequency ranges and time intervals (with p-values ranging from .036 to .359). Although jSDNN and HF presented similar correlations with behavioral performance, these two HRV parameters had distinct interactions with gender on theta/alpha oscillations. Among the 24 men recruited for the experiment, 9 were older than 30 years of age and 8 of them were classified to the Low-HRV group. The jSDNN-by-gender interaction could be confounded by age differences. Nevertheless, the correlations in Table 1 and partial correlations between jSDNN and theta/alpha oscillations reported in this section were not affected by statistical control over age differences.

In women, jSDNN was positively correlated with theta/alpha oscillations. It would be interesting to determine whether this strong association was specific to task-induced EEG reactions. Table 3 also lists ANOVA results for theta and alpha oscillations during the central eye-fixation (CEF) period within the -400 to -200ms interval from sentence onset (the central crosshair was shown on the computer screen at -500 ms). Within the CEF period, the jSDNN-by-gender effect was found to be significant in the theta, lower-alpha, and upper-alpha ranges. Figure 6 presents histograms of theta and lower-alpha power in the four groups during the CEF period. Theta synchronization was stronger among High-HRV women and Low-HRV men. Moreover, lower-alpha power was also weaker in these two groups compared with other participants. During the CEF period, lower- and upper-alpha desynchronization was stronger among Low-HRV women than among other participants, regardless of topographic localization. Among women, the partial correlations between jSDNN and EEG reactions during the CEF period were as follows: theta (.338 ± .106), lower-alpha (.440 ± .073), and upper-alpha (.451 ± .071). The corresponding correlations among men were as follows: theta (-.217 ± .109), lower-alpha (-.140 ± .098), and upper-alpha (-.093 ± .099). During the CEF period, theta synchronization was stronger and alpha desynchronization was weaker on average than those presented during the 100−600ms interval. Although the partial correlations were also significantly positive in women, the jSDNN-by-gender interaction should be interpreted

differently during the CEF period and post-onset intervals, especially for theta and lower-alpha oscillations.

Figure 6 about here.

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3. Discussion

Time-domain HRV parameters were found to be robust to both eyes-open and –closed conditions. The jSDNN index was able to differentiate women according to high arousal level (Low-HRV group) or high vagal tone (High-HRV group). When using short-term resting-state ECGs, all frequency-domain HRV parameters except for HF were less robust to eyes-closed and –open conditions. Although frequency-domain parameters based on ECGs recorded under the eyes-closed condition were sufficient to differentiate men from women, the relative HRV magnitudes among the four groups presented patterns opposite to those of the time-domain parameters. Thus, we strongly recommend that time-domain parameters be used to index short-term resting-state ECGs. When HRV parameters are sensitive to gender differences (e.g., pNN50), parameter values can be centered according to their mean values in the male and female groups, separately, before they are used as control variables in ANOVA (Schneider et al., 2015). The time- and frequency-domain parameters in Table 2 both indicate that the 26 young women exhibited greater parasympathetic activity than did the 24 men. In the literature, there has been considerable debate over whether gender differences modulate the relationship between HRV and cognition. Previously, researchers have recommended using nonlinear HRV parameters to predict gender-by-behavior interactions in attention, memory, RT, mood and cortisol level (Young and Benton, 2015). In this study, we demonstrated that the short-term resting-state jSDNN index can be used to differentiate EEG reactions of men and women. Besides, this index showed strong associations with behavioral performance and with theta/alpha oscillations in women. The jSDNN index may be considered an indicator of the degree of arousal in both vascular and cognitive systems during a stressful language task.

The simultaneous recording of blood-oxygen-level dependent (BOLD) responses and EEG reactions revealed that theta and alpha power were correlated with the hippocampal connection to the PFC and striatum in a recognition memory task. This in-turn suggests that theta oscillations direct the flow of information in hippocampal networks by coupling with higher frequencies, such as alpha activity, during the various stages of memory formation (Herweg et al., 2016). This result is consistent with findings conducted by others, and suggests that there may not be a clear functional distinction between theta and alpha oscillations, particularly for cognitive tasks which demand memory processing (Eckart et al., 2014). Our ANOVA results revealed insignificant gender effects in theta and alpha oscillations; that is, no significant differences were observed between men and women in terms of theta/alpha synchronization and desynchronization. Among women, High-HRV participants were responsible for most of theta synchronization activity during the 100−300ms post-onset interval, whereas Low-HRV participants were responsible for most of theta desynchronization activity during the 300−900ms post-onset interval, as shown in Figure 3. Alpha desynchronization in the women group was mainly contributed by those Low-HRV women. High-HRV women exhibited very little alpha desynchronization in the parieto-occipital regions during the 300−900ms post-onset interval, as shown in Figures 4 and 5. In light of the variations in EEG reactions among young women, the coupling of theta and alpha activity in the hippocampal-striatal-prefrontal networks should be investigated again by considering other factors that might have influence on young women.

The BIS is a neurophysiologic structure which is activated during a choice among several alternatives by use of behavioral strategies especially when participants have no explicit criteria for making a positive choice (Gray, 2000). In the EEG experiment, participants were required to decide whether sentences could be interpreted in one way or in more than one way without knowing specific criteria for correct judgment. We surmise that the 26 women could have initially withheld their reactions to the unambiguous sentences as evidenced by longer RTs, because they were unsure as to whether each of the unambiguous sentences actually had only one possible interpretation. It is possible that this situation activated the BIS, resulting in increased

cognitive arousal and attentional demands by an increase in RT. Sensitivity toward the BIS activation is closely linked to trait anxiety (Corr and Cooper, 2016; Gray, 2000); that is, the BIS dominates decision-making in individuals with high trait anxiety. Under the resting state, it has been shown that BIS scores on psychological questionnaires are associated with alpha power, and women usually have higher BIS and anxiety scores than men (Knyazev and Slobodskaya, 2003; Knyazev et al., 2004). It has also been demonstrated that HRV levels are associated with a balance between sympathetic and parasympathetic controls of the ANS. Thus, it would be reasonable to surmise that the jSDNN index also reflects a level of BIS involvement in the regulation of vascular and cognitive processes. Theta activity is also associated with the BIS (Moore et al., 2012), in that it reflects a mechanism for inhibiting irrelevant goals under uncertainty situations. Researchers have observed interdependency among the BIS, anxiety and theta activity during recognition of emotion-related stimuli such as facial emotions (Knyazev et al., 2008).

While stronger alpha desynchronization is associated with higher levels of attentional arousal and higher anxiety scores, it has been suggested that stronger theta-synchronization is associated with lower levels of arousal and lower anxiety scores (Knyazev et al., 2013). Our results revealed essential differences in alpha and theta oscillations between Low- and High-HRV women in the language task. More specifically, High-HRV women showed theta/alpha synchronization, whereas the Low-HRV women demonstrated strong theta/alpha desynchronization. These findings suggest that inhibitory control and attentional arousal may be lower in High-HRV women than in Low-HRV women. Although sympathetic regulation is highly associated with BIS activation, the dominance of parasympathetic regulation and high vagal tone may provoke a decrease in inhibitory control or may deactivate the BIS in women. We observed a strong dependency between HRV and alpha oscillations in women, but not in men. It is reasonable to hypothesize that this gender difference partially reflects differences in the role the BIS plays in regulating the behaviors of men and women. In this study, we did not measure individual BIS scores directly using psychological questionnaires. Therefore, the contribution of

the BIS to HRV and gender differences is only addressed tentatively here; further evidence is required to confirm this link.

The BIS and trait anxiety scores can be used to interpret EEG reactions between men and women. Exploratory factors are required to account for the discrepancy between Low- and High-HRV women who had comparable mean HR (66.585 vs 66.615 per sec) and mean RR (.918 vs .926 s), but different SDNN levels (.043 vs .086 s). Recent studies have found that the parasympathetic tone markers of HRV (e.g., pNN50, rMSSSD, and HF) are unaffected by menstrual phases, but sympathetic activity is enhanced as indicated by lower SDNN values during the luteal phase compared to the follicular phase (Pestana et al., 2018; Yazar, 2016). Other studies have also reported a predominance of parasympathetic activity during the proliferative (late follicular) phase and a predominance of sympathetic activity during the luteal phase (Brar et al., 2015; Tenan et al., 2014). As shown in Table 2, the two female groups differed in both time- and frequency-domain parameters with stronger parasympathetic activity in High-HRV women. It has been reported that the female brain operates in distinct neurophysiological modes during the menstrual cycle (Bazanova and Mernaya, 2008; Bazanova et al., 2014). Weak alpha desynchronization following the task onset is often associated with cognitive insufficiency and decreased task reactivity, which can be observed in the menstrual and premenstrual phases. During these phases, women are affected by enhanced psychoemotional tension associated with high initial arousal levels, rendering them unable to respond to additional cognitive loads (Brümmer et al., 2011). Strong alpha desynchronization can be observed in the luteal phase when cognitive efficiency is at its highest and psychoemotional tension is at its lowest (Bazanova et al., 2014). We hypothesize that EEG reactions to linguistic ambiguity may partially reflect the effects of female hormones among young women. On the other hand, HRV parameters in young women are also affected by age, body mass, respiration control, and recording length (Antelmi et al., 2004; Koenig and Thayer, 2016). These factors must also be taken into consideration for interpretation of the gender-by-jSDNN effect on theta/alpha oscillations.

4. Conclusion

This study took an initial step toward modeling EEG oscillatory activity using resting-state HRV parameters. In so doing, we found that jSDNN is positively correlated with theta and alpha oscillations among young women during the CEF and post-onset intervals. We hypothesize that the brain networks involved in the BIS differ between men and women, wherein the BIS may partially be influenced by female hormones in stressful language tasks. The limitations of the study include a relatively small sample size and unmatched ages between male and female groups in the computation of correlations. ANOVA results in Table 3 were not corrected for multiple comparisons because of the exploratory nature of this study and small sample size. We suggest that future investigations consider heterogeneity in young women when addressing interdependency among EEG reactions, cognition, and HRV. An experimental paradigm inducing mental stress might impose additional effects on theta/alpha desynchronization especially in the frontal and temporal regions, a condition in which interdependency between brain oscillatory activity and resting-state HRV could interact with cognitive control differently in men and women. We recommend that researchers also collect data on cortisol levels and sex-hormone when replicating our experiment using other stress-related tasks.

5. Experimental Procedures

5.1 Participants

A total of 50 right-handed, neurologically normal adults were recruited in the EEG experiment. All participants were undergraduate or postgraduate students without a history of speech/language or comorbid psychiatric and neurological disorders. Specifically, the sample included 26 women aged 19-30 (average age 23.46 ± 2.996) and 24 men aged 21-39 (average age 28.75 ± 4.152). All participants were native speakers of Mandarin Chinese but demonstrated some proficiency in English; that is, they had achieved acceptable scores on the TOEIC (> 550), GEPT (at least B1 or intermediate level), or TOEFL (> 57) test. All participants provided informed,

written consent prior to the experiment, thereby satisfying the requirements of the human participant research ethics committee/Institutional Review Board (IRB) at Academia Sinica, Taiwan.

5.2 Anxiety scale

The Chinese version of the State Trait Anxiety Inventory (cSTAI) was used to assess the explicit anxiety levels of participants (Shek, 1993; Spielberger, 1983). In the inventory, the 20-item STAI-Trait scale targets how participants generally feel, whereas the 20-item STAI-State scale assesses how participants feel at the time they took the test. State and trait anxiety scores were both considered in ANOVA analysis. On the cSTAI, participants were asked to rate themselves on each item based on a 4-point Likert scale, ranging from *almost never* to *almost always*. The STAI has been clinically validated in several studies (Gros et al., 2010; Hanin, 1989; Kvaal et al., 2005). The predictive validity of cSTAI was evaluated in Savostyanov et al. (2009) and Shek (1993) by comparing alpha oscillations between participants with high and low anxiety scores, and by correlating anxiety scores with scores on other scales of psychological well-being. The STAI has been shown to be socially and culturally dependent, that is, different ethnic groups present different norms. The 50 participants in this study were from the same cultural group; therefore, we used the cSTAI to evaluate relative differences among participants in terms of anxiety levels.

5.3 Experimental task

In the EEG experiment, participants completed the English language task by addressing 106 sentences, among which 52 sentences were semantically ambiguous (e.g., "They went to the bank yesterday;" which could mean that they went to a financial bank or to the river bank yesterday). Participants used a computer mouse to indicate whether a sentence presented on the computer screen could be interpreted in one way (left button) or more than one way (right button). Most ambiguous sentences were designed by a professional linguist (i.e., J. Evans) and revised in a pilot study. The pilot study was conducted with 40 participants (20 women; average age 25.90 ± 4.830), none of whom were later recruited for the EEG experiment, and included 256 English

sentences (207 of which were ambiguous). The unambiguous sentences were selected from a previous language study (Tsai et al., 2013). The 40 pilot participants performed the same task as that given in the main study, except that they responded to the unrevised pilot sentences. Following completion of the task, participants in the pilot study were interviewed to assess the clarity of task instruction, length of sentences, and duration of sentence presentation. On average, the pilot participants provided faster but less accurate responses to ambiguous sentences ($6161.60ms \pm 136.500$ and 0.60 ± 0.191) compared to unambiguous sentences ($7130.70ms \pm 1146.640$; 0.63 ± 0.150). Based on the response and feedback of participants in the pilot study, we selected 52 ambiguous sentences for the EEG experiment. Sentences selected for this study varied in length from 4 to 9 English words.

5.4 EEG/ECG recording

Following completion of the cSTAI, participants sat comfortably with eyes open in a chair positioned 60cm in front of a computer screen in a sound-insulated chamber. Electroencephalograms (EEGs) and electrocardiograms (ECGs) were recorded using an EEG cap with 132 Ag/AgCl electrodes (including 122 10-10 system EEG, the bipolar VEOG, HEOG, ECG, EMG, and six facial-muscle electrodes). The EEG electrodes were placed in 122 sites according to the extended international 10-10 system and were referred to as Cz with ground at FzA. Bipolar ECG electrodes were placed on the back of both the left and right hands of participants. Electrode resistance was maintained below 5 κΩ. Signals were amplified using *Neuroscan* amplifiers, with 0.1-100 Hz analog bandpass filtering and then digitized at 1000 Hz. Before performing the experimental task, the resting-state EEGs and ECGs were recorded for 4 min under the eyes-closed condition and for 4 min under the eyes-open condition. For these conditions, participants were told to relax in a chair and, for the eyes-open condition, they were instructed to fixate their gaze on a central cross on a 24.4×18.3 cm screen located in front of them (Gusnard and Raichle, 2001). The resting-state EEGs and ECGs were recorded from 2-5pm in the afternoon for most participants (46 out of 50). Only the resting-state 8 min ECGs were further processed in the analysis.

During the experiment, all sentences were presented in black and white (15 × 15 cm) on the same screen. After resting-state EEG/ECG registration, each participant self-reported her/his condition during the resting-state recordings using a 37-item self-referential thought scale (Knyazev and Slobodskaya, 2003). Participants were then provided with instructions that detailed how to perform the task. Before the experiment began, participants were allowed to practice the task several times with feedback given for incorrect responses; however, no feedback was provided during the experiment itself. The sentences used in the practice session were those that had not been selected from the pilot study. While performing the experimental task, a fixation cross was first presented in the center of the screen for 0.5 s, followed by a sentence for 8 s. Participants were instructed to make their decisions as quickly as possible. Ambiguous and unambiguous sentences were presented in random order, and the inter-stimulus-interval varied between 4 and 7 s.

5.5 Data processing

Resting-state ECGs were processed separately for eyes-closed and –open conditions using Kubios HRV-2.2 (Tarvainen, 2014; Tarvainen et al., 2014) for the time and frequency domain HRV parameters. Artifacts and linear trends were removed using the built-in filtering and detrending functions and, subsequently, the signals were manually examined for quality assurance purpose. The default HRV analysis settings included: sampling frequency (1000 Hz), detrending method (smoothing priors with the smoothing parameter 500), analysis method (fast Fourier transform based Welch's periodogram), and analysis window (60 s window with 50% overlap). For resting-state HRV analysis, time-domain parameters included the average inter-beat interval (mean RR), standard deviation of RR (SDNN), root mean square of successive RR differences (rMSSD), number of successive RR intervals that differed by more than 50ms (NN50), and the proportion of NN50 (pNN50). All of the above time-domain parameters were computed separately for eyes-closed and -open conditions (Brar et al., 2015; Chang et al., 2013; Mietus et al., 2012). The frequency-domain parameters included the normalized power of LF (Nu. LF; 0.04 – 0.15Hz) and HF (Nu. HF; 0.15 – 0.4Hz), both of which were divided by the difference

between total power and very low frequency power (0 - 0.04 Hz). For each participant, the HF and LF/HF ratio were also computed separately for eyes-closed and –open conditions.

The time-domain parameters were highly congruent between the eyes-closed and –open conditions. The correlation of mean RR between the two conditions was .971 (p < .001), and the correlation of SDNN between the two conditions was .802 (p < .001). The other time-domain parameters were also highly correlated between the two conditions: .959 (p < .001) for NN50, .962 (p < .001) for pNN50, and .883 (p < .001) for rMSSD. The correlation of mean heart rates (HRs) between the two conditions was .955 (p < .001). All frequency-domain parameters except HF power showed less congruency between the two conditions: .328 (p = .020) for Nu. LF, .330 (p = .019) for Nu. HF, .332 (p = .019) for the LF/HF ratio, and .714 for HF (p < .001). Due to congruence between the two conditions, mean RR, SDNN, NN50, pNN50, rMSSD and HF were re-calculated for each participant using 8 min ECGs. Because RR and HR parameters presented an inverse relationship, standard HRV analysis may be mathematically biased particularly when participants differ in terms of mean HR, a parameter which exhibits considerable heterogeneity between genders and the age groups used in this experiment (Antelmi et al., 2004; Sacha and Pluta, 2008). For example, the correlation between the 8 min mean RR and mean HR was −.989 (p < .001). Other parameters significantly correlated with mean HR included NN50 (−.483; p < .001) and pNN50 (−.583; p < .001). The values of HF, rMSSD and pNN50 are known to be higher in women than in men in all age groups (Antelmi et al., 2004). In other words, these parameters might not demonstrate the unique HRV effect in ANOVA due to a confounding effect with gender.

The SDNN parameter is the most frequently used time-domain parameter (Haensel et al., 2008). The 8 min SDNN was divided by mean RR (Kuusela, 2012; Sacha and Pluta, 2008; Sacha, 2014), a standardization procedure which partially removed the mathematical bias but did not impart any physiological variability to HRV. Existing literature refers to the adjusted SDNN (jSDNN hereafter) as the coefficient of variation in comparisons between data sets that have widely different means. As a result, this adjusted SDNN value is recommended for studies on

HRV (Kuusela, 2012). The jSDNN presented a correlation of .856 (p < .001) with HF, .426 (p = .014) with pNN50, and .923 (p < .001) with rMSSD. We applied the median of jSDNN indices to divide the 50 participants into two groups. For ease of exposition, participants with jSDNN indices below the median are collectively referred to as the Low-HRV group, and those with jSDNN indices above the median are referred to as the High-HRV group. The advantage of the jSDNN index is that it provides a ready-to-use control variable in ANOVA, and is less dependent on mean HR and gender. In this study, SDNN presented the following correlations: -.182 (p = .205) for mean HR, .250 (p = .080) for mean RR, and jSDNN presented the following correlations: .049 (p = .733) for mean HR, and .015 (p = .919) for mean RR.

EEGs were processed using EEGLAB and band pass filtered between 1 - 50 Hz. For time-frequency analysis, event-related spectral perturbations (ERSPs) were computed using the EEGLAB toolbox (Delorme and Makeig, 2004). Wavelet transformation (using the *Morlet* wavelet) was applied to time-frequency representation of the EEG time series. On-going EEGs were epoched from -2 s pre-stimulus to 1.5 s post-stimulus onset. Artifacts resulting from eye movements, blinks, muscle noise, and line noise were estimated using independent component analysis (ICA) (Makeig et al., 1996). To differentiate brain activity from artifacts, we employed an automatic approach based on reference signals in the VEOG, HEOG, and ECG channels. For this, a significantly high multiple correlation value ($R^2 > 0.9$) between ICA scores and reference signals indicated that a given ICA component was mainly a result of artifacts. In such cases, the component scores were adjusted for artifacts based on multiple regression analysis. Artifact-corrected EEGs at (-1.6, -0.85)-s before the stimulus onset were selected as the baseline for adjusting ERPs and ERSPs. This interval was prior to the central eye-fixation period and sentence onset. Before averaging ERSPs across channels, we partitioned scalp channels into eleven regions: left-frontal (10 channels), midline-frontal (11), and right-frontal (10); left-temporal (17), and right-temporal (17); left-central (9), midline-central (9), and right-central (9); left-parieto-occipital (9), midline-parieto-occipital (12), and right-parieto-occipital (9). These regions were defined according to the functional anatomy of the cortex (Başar, 2012b). The EEG

electrodes located in the various scalp regions can be found in Chien et al. (2016). Functional homogeneity in EEG signals from these regions has been validated in a variety of experiments (Savostyanov et al., 2009; Tsai et al., 2013; Tseng et al., 2015). ERSPs were averaged across channels within each region for each participant, and theta (5-8Hz), lower-alpha (8-10Hz), and upper-alpha (10-12Hz) oscillations were extracted for statistical analysis.

In each time-frequency interval, repeated-measures ANOVA was used to test within-participant differences among the eleven scalp regions and between-participant differences among genders. In the ANOVA layout, participants were subjected to repeated ERSP measures across the eleven scalp regions. Repeated-measure ANOVA assumes normality and sphericity. The ERSPs in theta and alpha ranges were averaged across channels and time intervals (e.g., 300−600 ms post-onset). A violation of sphericity can increase the likelihood of Type-I errors. Therefore, in repeated measures ANOVA, within-participant effects were evaluated using the Greenhouse-Geisser test, which provides more conservative control over Type-I errors when the assumption of sphericity is violated. In addition, the eleven scalp regions were included as the within-participant factor, and gender was included as the between-participant factor. The median split of jSDNN indices into High-HRV and Low-HRV groups as well as the median splits of cSTAI-State and −Trait scores into high and low anxiety groups were included as control variables. All analysis was implemented using IBM SPSS Statistics 20.

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Table 1: Reaction times in millisecond and response accuracy rates in men and women along with the average anxiety scores in different groups. Standard deviations are given in parentheses.

Type	Men				Women			
	High HRV	Low HRV	Total	Corr.	High HRV	Low HRV	Total	Corr.
No. of participants	10	14	24		15	11	26	
No. of sentences practiced	14.400 (14.033)	6.929 (6.833)	10.042 (10.845)	.232	13.000 (14.629)	13.273 (16.668)	13.115 (15.198)	-.132
Reaction time (Ambiguous)	4715.381 (966.869)	4876.956 (805.888)	4809.633 (859.948)	-.168	4598.869 (877.786)	5163.281 (723.008)	4837.659 (849.380)	-.343
Reaction time (Unambiguous)	4640.302 (1201.533)	4765.581 (1104.653)	4713.382 (1121.878)	-.160	4647.510 (942.497)	5334.804 (860.336)	4938.288 (955.735)	-.446*
Accuracy rate (Ambiguous)	.583 (.097)	.651 (.156)	.623 (.137)	-.274	.659 (.157)	.729 (.114)	.689 (.142)	-.393*
Accuracy rate (Unambiguous)	.793 (.145)	.802 (.159)	.798 (.150)	-.008	.786 (.154)	.727 (.185)	.761 (.166)	.232
STAI-State	28.400 (8.249)	30.714 (6.305)	29.750 (7.103)	-.009	32.467 (7.190)	32.091 (7.162)	32.308 (7.036)	-.070
STAI-Trait	36.700 (8.603)	39.929 (6.403)	38.583 (7.401)	-.167	40.933 (7.601)	42.636 (8.429)	41.654 (7.843)	-.154

Note: The correlations between jSDNN and behavioral performance are listed in the last column for men and women. The significant correlations with $p < .05$ are marked with asterisks.

Table 2: The resting-state HRV parameters.

HRV	Men			Women			Corr.	
	High HRV	Low HRV	Total	High HRV	Low HRV	Total	STAI-State	STAI-Trait
NN50 count (8 min)	148.700 (80.990)	99.429 (78.039)	119.958 (81.392)	200.267 (89.049)	153.636 (76.976)	180.538 (85.806)	.337*	.202
pNN50 % (8 min)	28.400 (16.408)	19.131 (15.593)	22.993 (16.265)	39.812 (21.159)	30.000 (15.226)	35.661 (19.181)	.337*	.198
rMSSD sec (8 min)	.086 (.043)	.042 (.012)	.061 (.036)	.108 (.040)	.049 (.012)	.083 (.043)	.103	-.151
HF sec^2 (8 min)	.003 (.003)	.001 (.001)	.002 (.002)	.004 (.003)	.001 (.001)	.003 (.003)	.063	-.173
Nu. LF % (closed 4 min)	51.491 (17.100)	48.946 (18.896)	50.006 (17.829)	41.303 (12.880)	32.900 (16.505)	37.747 (14.825)	-.280*	-.106
Nu. HF % (closed 4 min)	48.405 (17.099)	50.925 (18.902)	49.875 (17.831)	58.501 (12.898)	67.026 (16.508)	62.108 (14.853)	.281*	.108
LF/HF (closed 4 min)	1.391 (1.132)	1.244 (.852)	1.305 (.957)	.777 (.352)	.603 (.513)	.703 (.427)	-.278*	-.114
Nu. LF % (open 4 min)	45.248 (15.973)	54.717 (16.803)	50.771 (16.798)	42.578 (12.601)	44.509 (18.763)	43.395 (15.188)	-.261	-.094
Nu. HF % (open 4 min)	54.620 (15.908)	45.147 (16.798)	49.094 (16.771)	57.233 (12.573)	55.429 (18.742)	56.470 (15.161)	.261	.095
LF/HF (open 4 min)	.983 (.619)	1.608 (1.218)	1.347 (1.043)	.843 (.492)	1.158 (1.202)	.976 (.860)	-.262	-.092

Note: The correlations between HRV parameters and state and trait anxiety scores are listed in the last 2 columns of the table. The significant correlations with $p < .05$ are marked with asterisks.

Table 3: ANOVA results on ERSPs during different time intervals. The within-participant effect refers to the scalp region effect, and the between-participant effects refer to the gender, jSDNN and trait anxiety effects. Significant interactions observed are region-by-gender-by-jSDNN, region-by-gender-by-trait, and gender-by-jSDNN. Note: The subscript numbers positioned to the right of F letters are the degrees of freedom of ANOVA F values. The listed F values are those with $p \leq 0.05$.

| Freq. ranges	Intervals (msec)	Region	Region-by-Gender-by-jSDNN	Region-by-Gender-by-Trait	Gender-by-jSDNN
4-8Hz	[-400 to -200]	$F_{2.4,103.1} = 14.330$; $p < .001$	$F_{2.4,103.1} = 3.490$; $p = .027$		$F_{1,43} = 9.098$; $p = .004$
	[100~300]		$F_{2.2,95.3} = 3.579$; $p = .028$		$F_{1,43} = 13.328$; $p = .001$
	[300 ~600]	$F_{2.2,96.4} = 24.073$; $p < .001$			$F_{1,43} = 10.460$; $p = .002$
	[600~ 900]	$F_{2.2,96.0} = 27.353$; $p < .001$			$F_{1,43} = 7.674$; $p = .008$
8-10Hz	[-400 to -200]	$F_{2.0,84.9} = 4.887$; $p = .010$	$F_{2.0,84.9} = 4.084$; $p = .021$		$F_{1,43} = 10.530$; $p = .002$
	[100~300]	$F_{2.1,92.2} = 22.942$; $p < .001$	$F_{2.1,92.2} = 2.999$; $p = .051$	$F_{2.1,92.2} = 2.996$; $p = .051$	$F_{1,43} = 12.167$; $p = .001$
	[300 ~600]	$F_{2.3,100.7} = 67.248$; $p < .001$		$F_{2.3,100.7} = 3.693$; $p = .022$	$F_{1,43} = 7.005$; $p = .011$
	[600~ 900]	$F_{2.5,105.7} = 68.010$; $p < .001$		$F_{2.5,105.7} = 5.203$; $p = .004$	$F_{1,43} = 6.350$; $p = .016$
10-12Hz	[-400 to -200]	$F_{2.3,97.1} = 45.044$; $p < .001$		$F_{2.3,97.1} = 4.418$; $p = .011$	$F_{1,43} = 9.821$; $p = .003$
	[100~300]	$F_{2.3,97.1} = 45.044$; $p < .001$		$F_{2.3,97.1} = 4.418$; $p = .011$	$F_{1,43} = 10.053$; $p = .003$
	[300 ~600]	$F_{2.5,108.0} = 87.524$; $p < .001$		$F_{2.5,108.0} = 4.945$; $p = .005$	$F_{1,43} = 7.048$; $p = .011$
	[600~ 900]	$F_{2.8,119.4} = 91.773$; $p < .001$		$F_{2.8,119.4} = 7.759$; $p < .001$	$F_{1,43} = 5.370$; $p = .025$
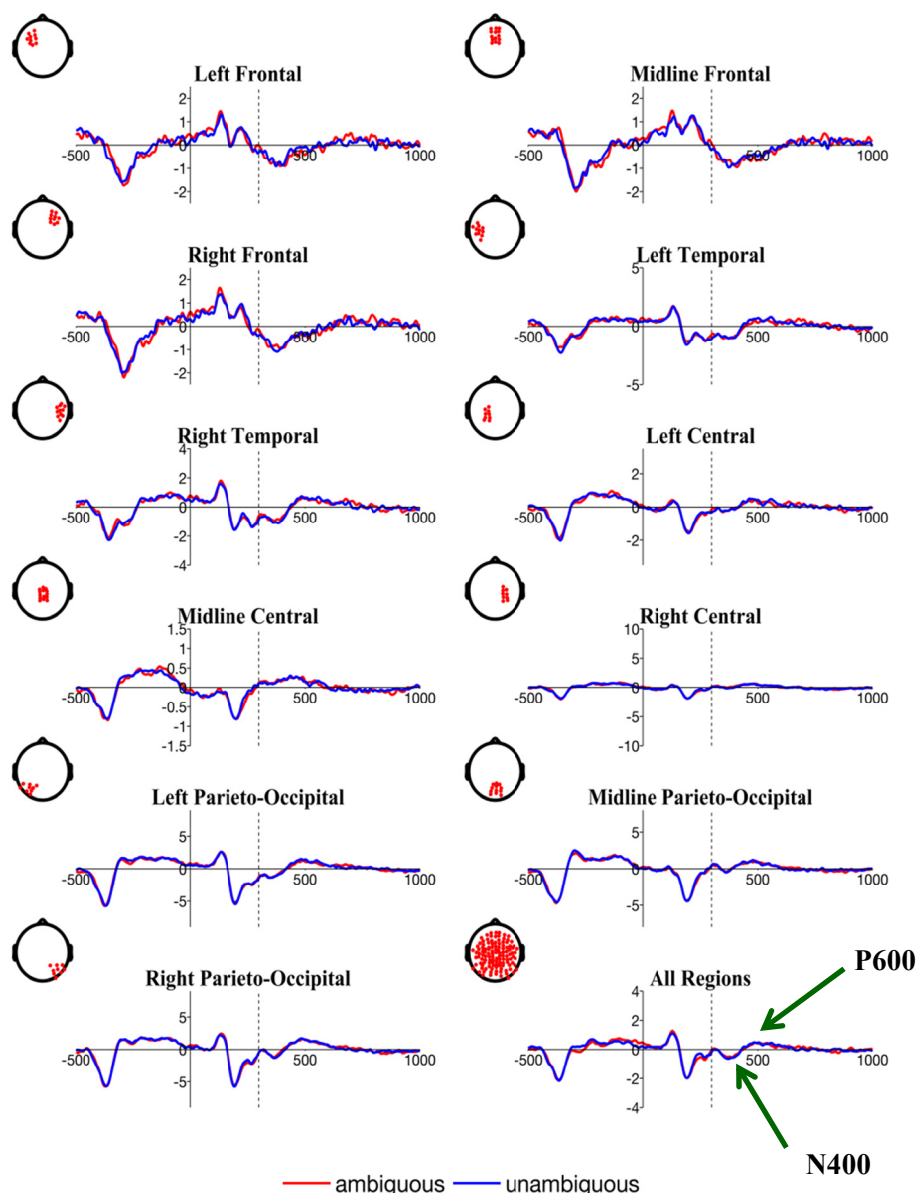
Figure 1: The baseline corrected ERP plots for unambiguous (blue) and ambiguous (red) sentences in the 11 scalp regions. EEG channel locations are shown in the left-hand side of each plot. The vertical axis shows the ERP voltage (μV) and the horizontal axis shows the time in millisecond. The two green arrows indicate locations of the N400 and P600 components in the ERP plots. The N400 component is pronounced in the frontal, temporal and parieto-occipital regions, and the P600 component is pronounced in the temporal and parieto-occipital regions.
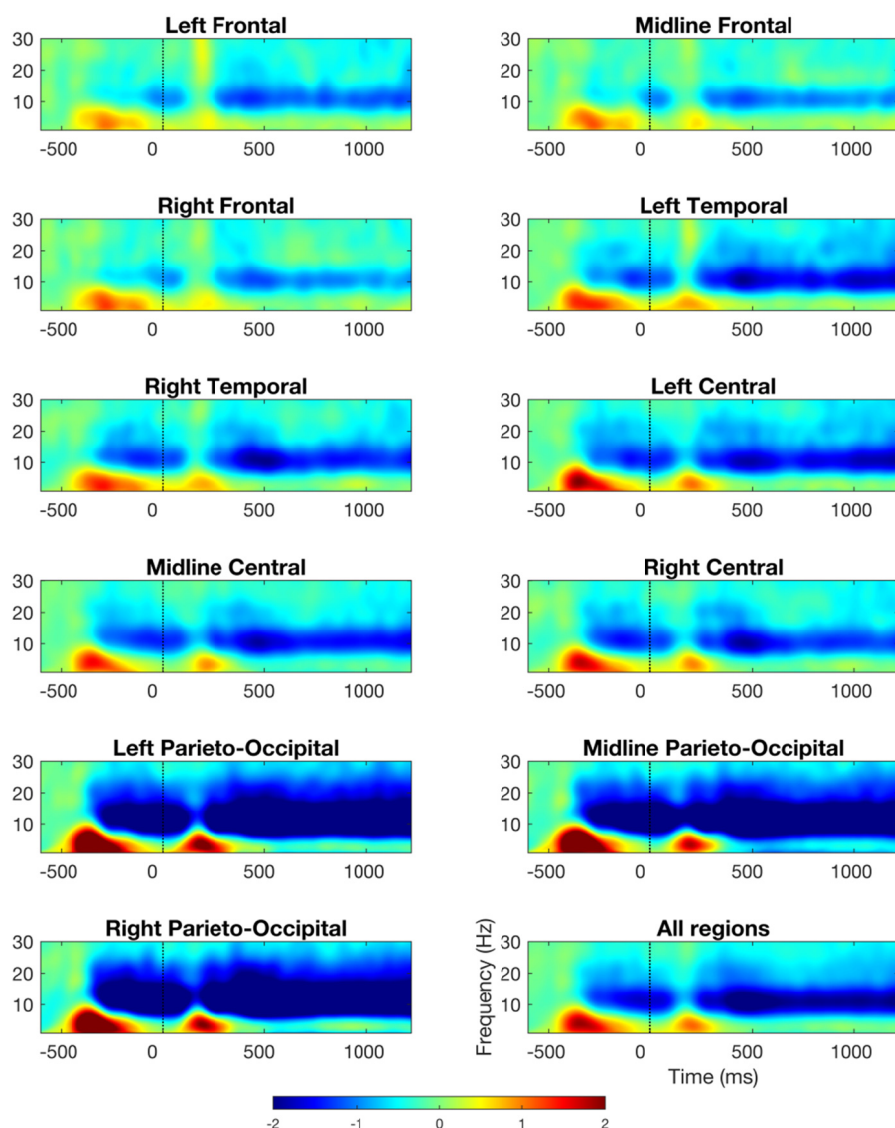
Figure 2(A): The baseline corrected ERSP plots in the 11 scalp regions for the unambiguous sentences. In each ERSP plot, the vertical axis shows the frequency (1-30Hz), and the horizontal axis shows the time in millisecond (-500 to 1200 ms). The locations of EEG electrodes corresponding to different regions are the same as those shown in Figure 1. The red color denotes power increase (synchronization) compared with the baseline, and the blue color denotes power decrease (desynchronization) compared with the baseline.
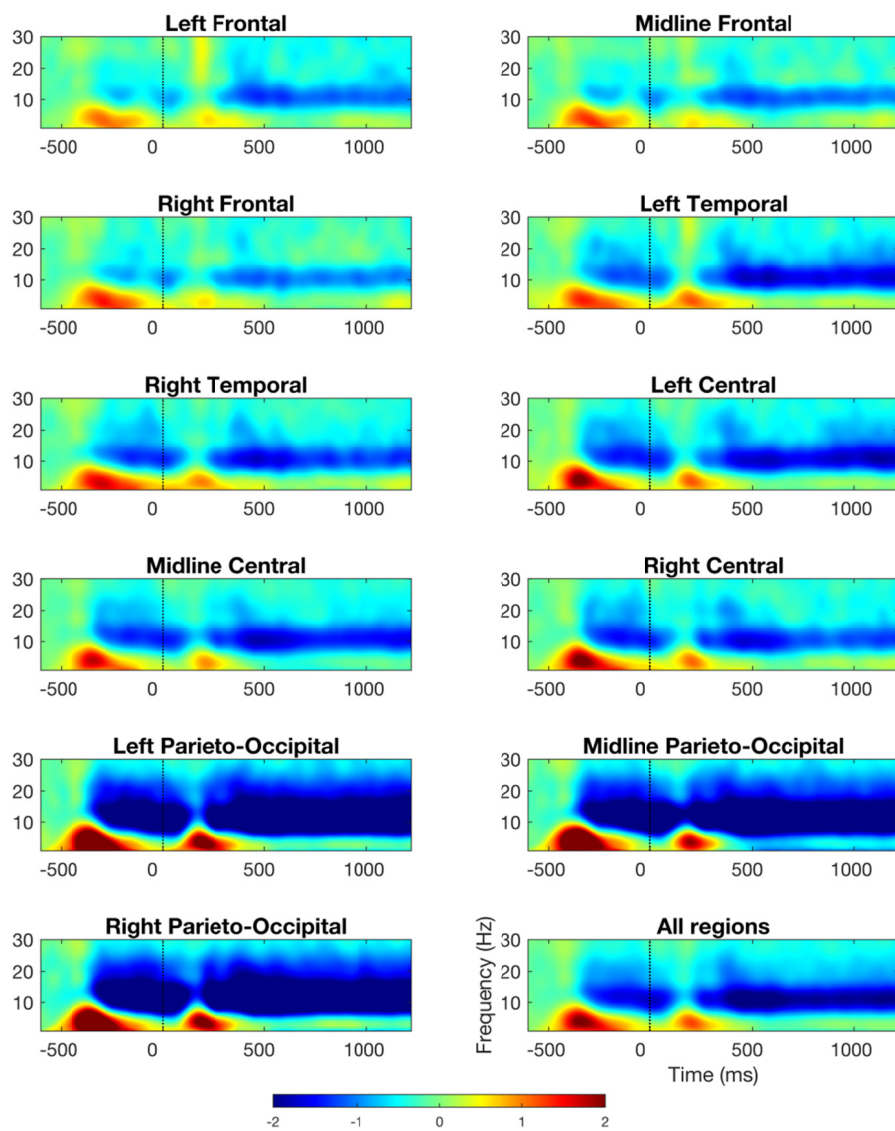
Figure 2(B): The baseline corrected ERSP plots in the 11 scalp regions for the ambiguous sentences.

(A)
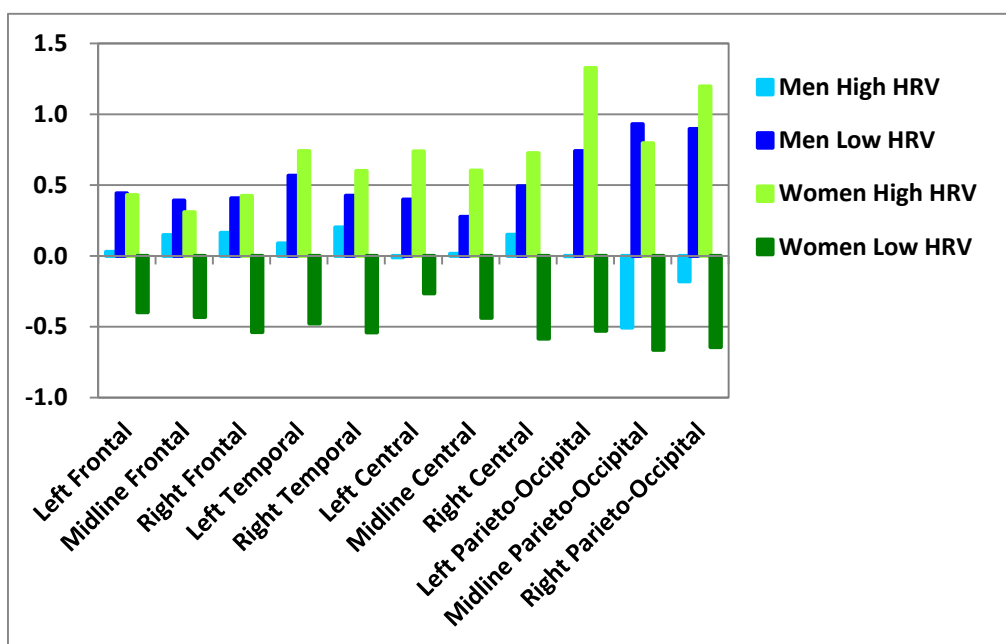
(B)
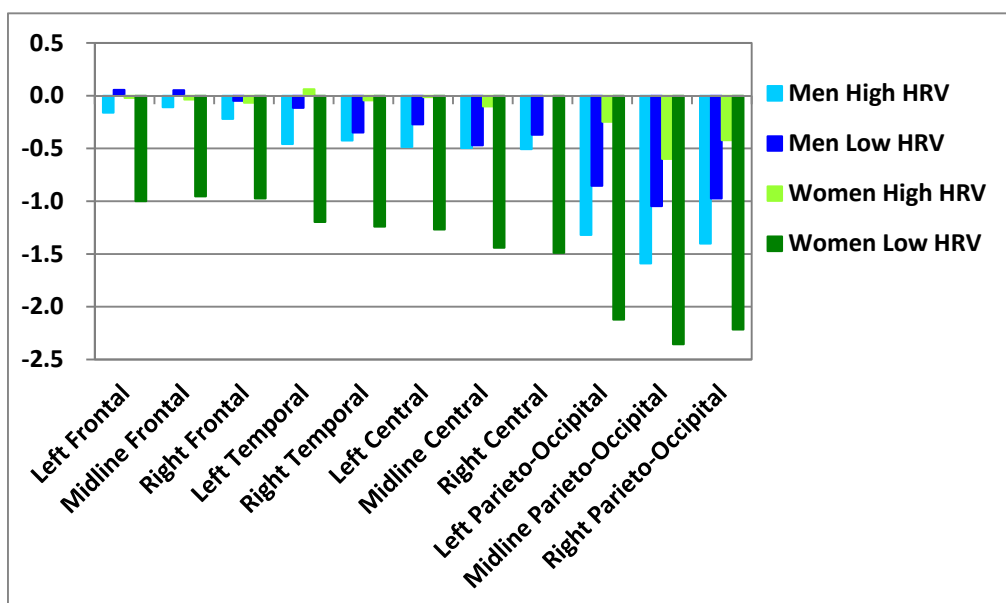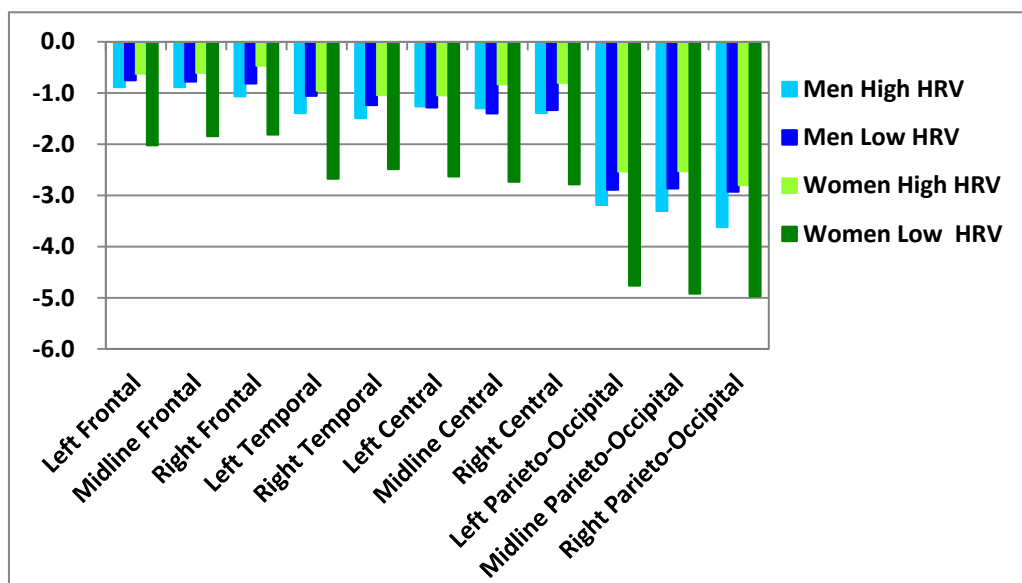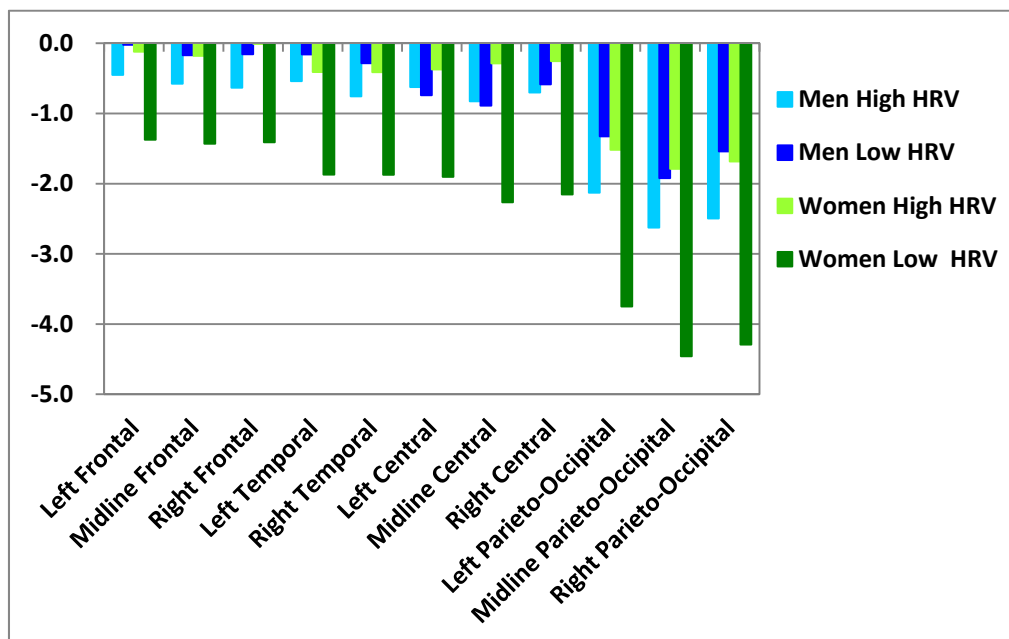

Figure 3: Average theta power during the (A) 100−300ms and (B) 300−600ms post-onset intervals in different scalp regions for the 4 groups classified 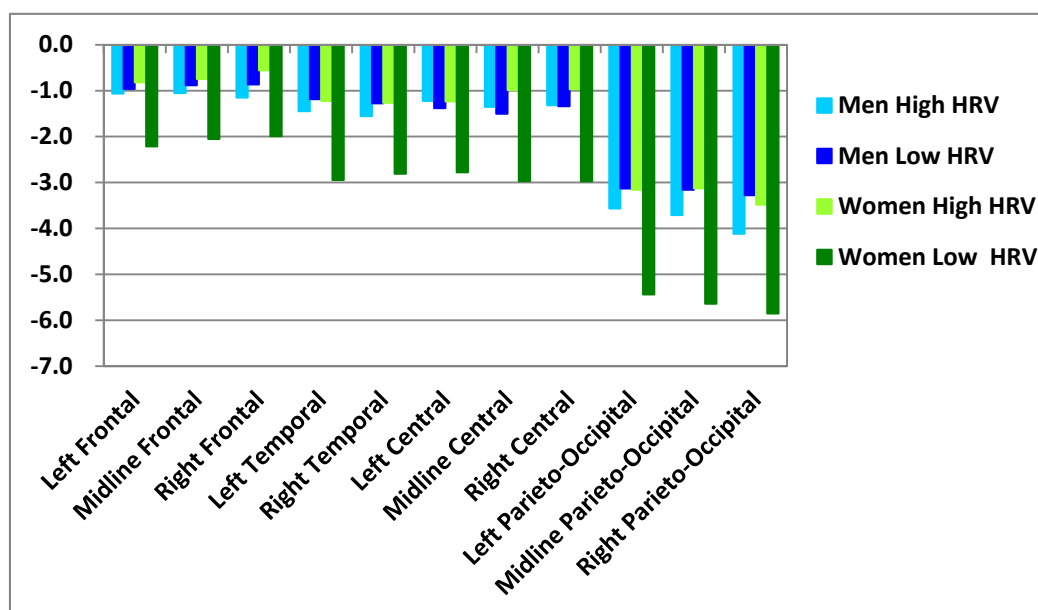according to gender and the median split of jSDNN indices. There were 10 men and 15 women, respectively, classified to the High-HRV group (with relatively high jSDNN values). The positive value in the vertical axis denotes a power increase compared with the baseline, and the negative value denotes a power decrease.

(A)
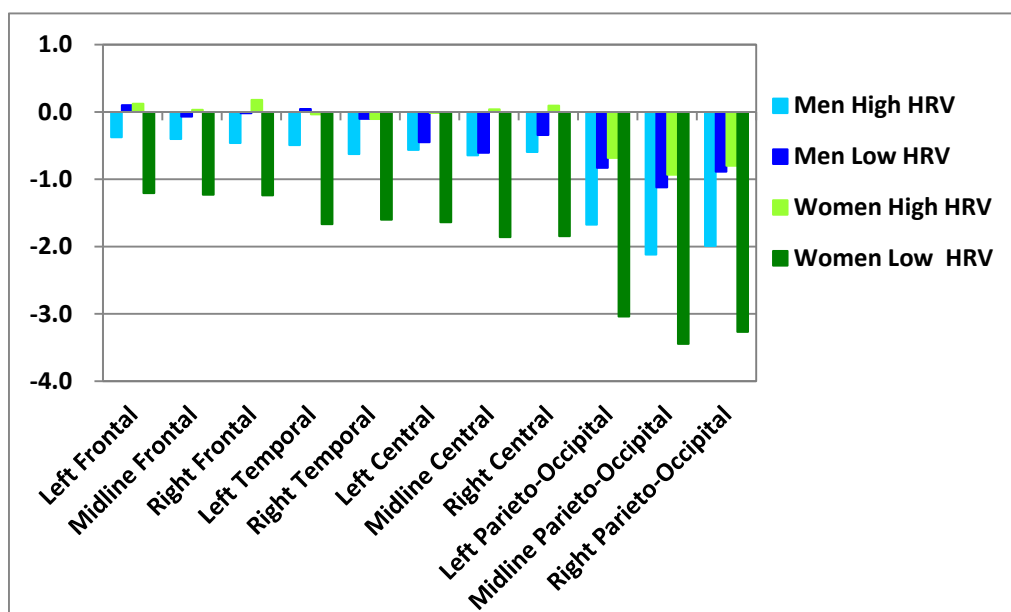
(B)

Figure 4: Average lower-alpha power during the (A) 100−300ms and (B) 300−600ms post-onset intervals in different scalp regions for the 4 groups classified according to gender and the median split of jSDNN indices.
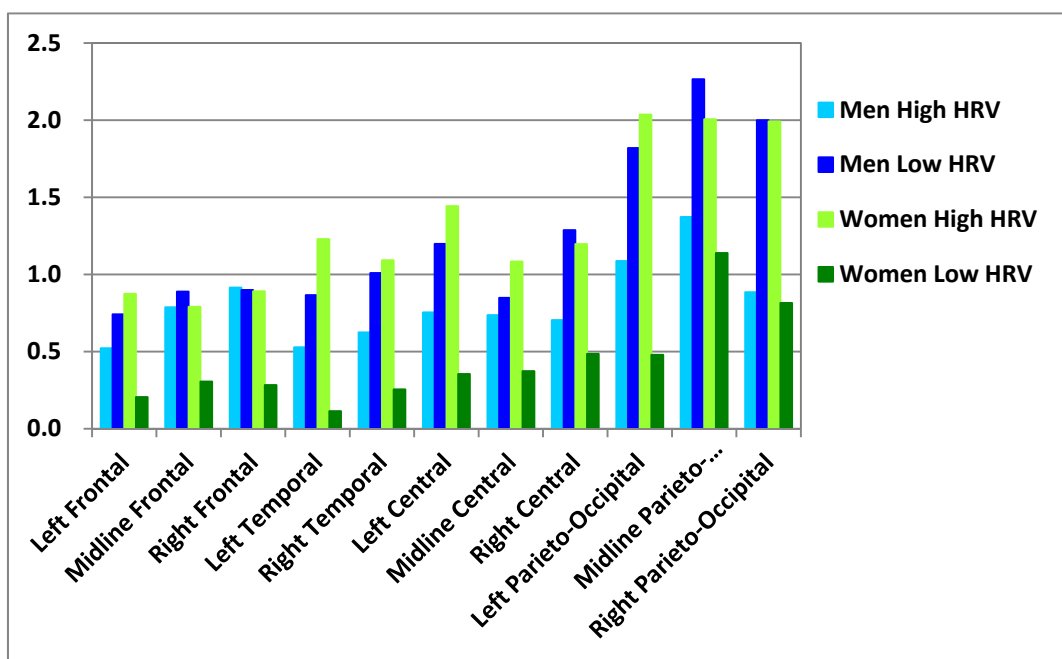
(A)

(B)

Figure 5: Average upper-alpha power during the (A) 100−300ms and (B) 300−600ms post-onset intervals in different scalp regions for the 4 groups classified according to gender and the median split of jSDNN indices.
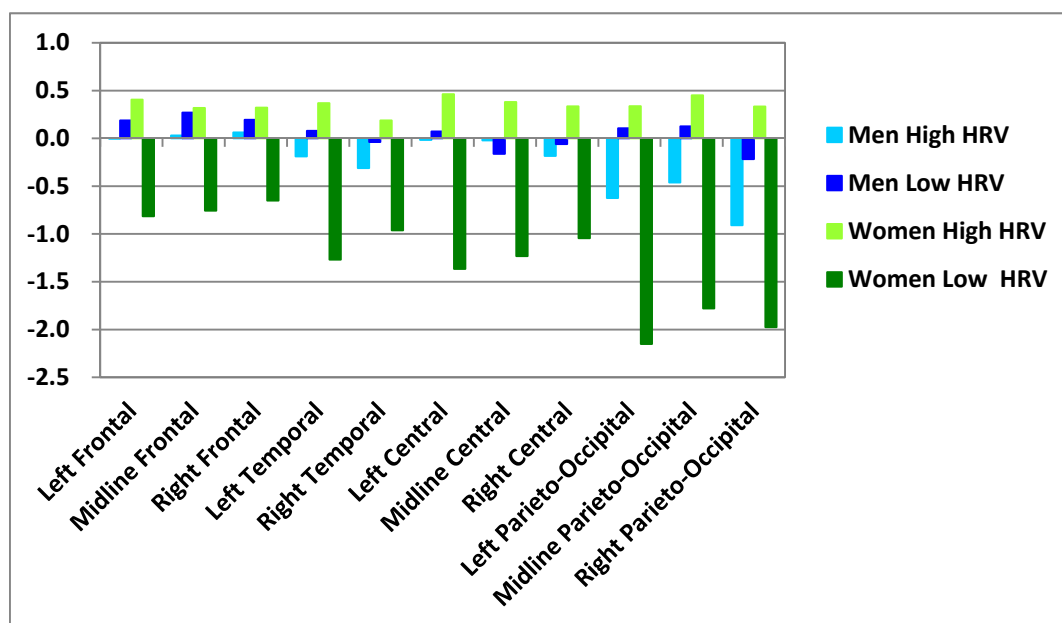
(A)

(B)

Figure 6: Average (A) theta power and (B) lower-alpha power during the -400 to -200ms CEF period in different scalp regions for the 4 groups classified according to gender and the median split of jSDNN indices.