

RESEARCH ARTICLE

EEG Resting Activity in Highly Sensitive and Non-Highly Sensitive Persons

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Sensory processing sensitivity (SPS) is a trait correlated with increased sensitivity to internal and external stimuli. fMRI studies indicate that increased activation in areas associated with attention, empathy, and higher-order visual processing correlate with high SPS. We used electroencephalography frequency power spectra in four frequency bands (delta, theta, alpha, and beta) during resting state to examine differences between highly sensitive and non-highly sensitive persons. Results show that high SPS relates to higher absolute power in all frequency bands, pointing to higher activity of cortical pyramidal cells. Additionally, this trait similarly relates to higher relative power in the delta and lower relative power in the alpha band, suggesting that high SPS persons are better able to shift attention from the external environment to the internal state.

Keywords: EEG spectral power, sensory processing sensitivity, Resting Activity, Highly Sensitive Persons, Non-Highly Sensitive Persons

Sensory processing sensitivity

Sensory processing sensitivity (SPS) refers to a personality trait correlated with increased sensitivity to both internal and external stimuli. The SPS trait is at least partially innate (Aron et al., 2010), and studies have shown that it is present in over 100 animal species (Wolf, Doorn, & Weissing, 2008). Moreover, it has been reported that SPS is found in approximately 20% of the individuals of a species (Wolf et al., 2008). From an evolutionary perspective high SPS reflects a risk-averse strategy, one in which the individuals analyze the environment in detail before acting. Thus, they possess an advantage in identifying potential dangers with low SPS reflecting a risk-taking strategy, characterized by acting as fast as possible in order to

seize transient opportunities. Therefore, it becomes apparent why the trait is present only in a quarter of all individuals: while SPS provides benefits for survival, it is accompanied by high metabolic costs, and would yield a low pay-off if it were to form the majority (Wolf et al., 2008).

These distinctions are closely related to Gray's personality theory, which posits the existence of two different personality dimensions, namely the behavioural inhibition system (BIS) and the behavioural activation system (BAS). The BIS reflects high sensitivity to punishment, novelty, and nonreward, leading to higher inhibition of reward-seeking behaviour, while the BAS reflects the opposite dimension, with higher sensitivity to reward and increased goal-oriented behaviour (Carver & White, 1994).

Although it cannot be claimed that there is a perfect overlap between Gray's two personality dimensions and the two SPS extremes, it is evident

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that the risk-averse strategy corresponding to high SPS is similar to the BIS, with both being characterized by an inhibition of behaviour and the adoption of a “pause-to-think” strategy, and that the risk-taking strategy corresponding to low SPS is similar to the BAS, in this case both being described by a fast-acting, reward-seeking behaviour.

Highly sensitive persons (HSP) adopt the same strategy of pausing to analyze, and thus show greater response to environmental stimuli (e.g., bright lights, loud noises) and social stimuli (e.g., others’ moods), as well as increased responsiveness to subtle stimuli, compared to people with low SPS (non-highly sensitive persons/non-HSP; Aron, Aron, & Jagiellowicz, 2012). This behaviour has been initially attributed to other personality traits, such as introversion or emotionality. However, Aron and Aron (1997) have demonstrated that, although correlated with these, SPS is an independent trait, and have developed a 27-item scale for assessing it.

Neuroimaging correlates of SPS

Evidence from functional magnetic resonance imaging studies (fMRI) revealed a positive correlation between HSP scores obtained on the aforementioned scale and activation in brain areas associated with attention and action planning, awareness, empathy, integration of sensory information, and higher-order visual processing (Acevedo et al., 2014; Jagiellowicz et al., 2011). SPS has also been investigated in relation to a modulation effect of cultural differences in fMRI neural response (Aron et al., 2010). Most recently, Chen and coworkers reported that activity in the precuneus during rest suppressed the effect of dopamine-related genes on SPS (Chen et al., 2015). The precuneus is involved in regulation and integration of higher-order information involving visuo-spatial imagery, episodic memory, and emotional stimuli. Thus, one could assume that resting state activity significantly determines brain activation in response to external and internal stimuli in SPS as reported in the fMRI studies mentioned above.

To our knowledge, no studies investigating brain state correlates of SPS using

electroencephalography (EEG) have been conducted so far. However, the above fMRI studies suggest that different personality traits are reflected by different patterns of resting-state brain oscillations (Hagemann et al., 1999). In addition, changes in the power of two frequency bands, namely delta and alpha, have been linked to two complementary attentional systems. More specifically, increases in the delta band power from rest to task, accompanied by decreases in the alpha band power have been proposed to underlie an increased internal attentional focus, while the opposite pattern (decreases in the delta band power, and increases in the alpha band power), are suggested to underlie an increased focus of attention to external stimuli (Harmony, 2013).

In general, both alpha and delta activity are high during rest. Nevertheless, the two rhythms are related to different cognitive processes. Studies using simultaneous EEG-fMRI recordings have shown that resting state networks associated with higher cognitive functions, such as self-reflection, correlate positively with higher EEG frequency bands (i.e., alpha) and negatively with lower EEG frequency bands (i.e., delta; Jann, Kottlow, Dierks, Boesch & Koenig, 2010; Laufs et al., 2003). Additionally, alpha oscillations have been shown to mediate inhibition in the brain (Goldman, Stern, Engel & Cohen, 2002), while delta oscillations appear to be related to basic motivational processes, and thus might be involved in the constant scanning for both internal and external cues which might be signalling either threat or reward (Knyazev, 2012).

Current study

The present study aims to bridge the gap between degrees of SPS and underlying neural processes by investigating whether differences in SPS are related to differences in EEG spectral power during rest. We hypothesized that there should be a significant difference in EEG spectral power between highly sensitive and non-highly sensitive persons.

On the one hand, since persons high in SPS perceive stimuli more intensely, they should have a higher level of arousal and therefore increased EEG spectral power. On the other hand, different levels of

stimulus perception are at least partially attributable to the amount of attention paid to the respective stimulus (Corbetta & Shulman, 2002; Hopfinger & Mangun, 1998; Tse, 2005), thus the difference in spectral power should be mainly present in those frequency bands associated with attentional control (delta and alpha bands). Furthermore, since HSP have shown increased activation in brain areas related to attention (Acevedo et al., 2014), if this translates into an increased ability of controlling attention then highly sensitive persons are expected to have an increase in delta band power and a decrease in alpha band power. Subsequently, if the increased activation reflects a higher recruitment of brain areas due to poor attentional control, the opposite pattern is expected.

Methods

Participants

Sixty students (31 women, age range: 18–55, $M_{age} = 21.48$, $SD_{age} = \pm 5.13$) from Jacobs University Bremen were selected via convenient sampling and were screened for this study. 56 of them were undergraduate students, three graduate, and one post-graduate. There were 32 participants from Europe, 19 from Asia, five from North America, three from South America, and one from Africa. Based on HSP scores, ten participants from each extreme of the sample (20 participants in total, 13 women [9 women in the HSP group], age range: 19–55, $M_{age} = 22.35$, $SD_{age} = 7.81$) who agreed to participate in the EEG recording were selected from the initial sample. All participants gave their informed consent and were treated in accordance with the Declaration of Helsinki and local ethics guidelines. The study was also approved by the thesis supervisors with respect to ethical standards. Participants were reimbursed for their participation with either course credits or candy. In addition, all participants entered a raffle which had as reimbursement a 25€ Amazon voucher.

Questionnaires

All participants filled in the 27-item HSP scale (see Appendix 1). In addition, two items measuring introversion, three items measuring neuroticism, and

21 items measuring encoding styles (Lewicki & Czyzweska, 2001) were included in the questionnaire battery (see Appendix 1). The introversion and neuroticism items were included due to previous studies showing that these traits correlate with the HSP scale and might distort its scores (Aron & Aron, 1997).

EEG recording and data analysis

Resting state EEG recordings were obtained from 20 participants (10 HSP, 10 non-HSP). Participants were seated in a dark chamber and asked to keep their eyes closed, minimize movement, and relax for 15 minutes. EEG signals were recorded continuously for 15 minutes, using 32 Ag-AgCl BioSemi Active electrodes, and the common mode sense (CMS) and driven right leg (DRL) electrodes. The electrodes were set at the following locations: AF3, AF4, Fp1, Fp2, F3, F4, F7, F8, Fz, FC1, FC2, FC5, FC6, Cz, C3, C4, CP1, CP2, CP5, CP6, T7, T8, P3, P4, P7, P8, Pz, PO3, PO4, O1, O2, Oz. In addition, 4 electrodes (EX1, EX2, EX3, and EX4) were used to track potential eye movements and ensure that participants rested with their eyes closed. Electrode impedances were kept below 2500 Ω . Data were recorded at a sampling rate of 2048 Hz with the ActiView (version 6.05) software. Raw data is publicly available on OSF (Open Science Foundation, https://osf.io/pgtu6/?view_onl).

Data were analyzed with EEGLAB (version 11.0.5.4b; Delorme & Makeig, 2004), and MATLAB (version 8.3.0.532; 2014) software. After recording, data were filtered offline with a 0.5 Hz high-pass filter, and a 30 Hz low-pass filter with a finite impulse response (FIR) filter. Subsequently, the data were downsampled to 256 Hz and re-referenced to the average of electrodes T7 and T8 (Alhaddad, Kamel, & Malibary, 2012). Data were first filtered and then downsampled to avoid aliasing artifacts. Each 15-minute segment was segmented into 3s epochs, leading to 300 epochs per participant. Afterwards, epochs with artifacts (eye movements and muscle artifacts) were excluded through visual inspection. Bad electrodes were defined as the ones for which more than 5% of the epochs were excluded, and they were interpolated using the “eeg_interp” MATLAB function for standard spherical interpolation (Perrin,

Pernier, Bertrand, & Echallier, 1989). On average, 59 epochs were excluded per participant (1176 epochs excluded in total).

Four frequency bands (delta: 0.5–4 Hz, theta: 4–8 Hz, alpha: 8–13 Hz, and beta: 13–30 Hz) were defined, and a frequency domain analysis of absolute and relative power in each frequency band was conducted using the Fast Fourier Transform (FFT) algorithm on the epoched data. A 769-point taper Hanning window was applied to each trial prior to the FFT algorithm, in order to prevent edge artifacts from contaminating the results (Oppenheim, Schafer & Buck, 1999, p.488). The FFT was used to calculate absolute power for each trial, for each frequency band, at each of the 32 electrodes. The trials at each electrode were randomly split in half for each participant and mean absolute power ($\mu\text{V}^2/\text{Hz}$) in each frequency band was computed for both halves. Relative power (%) was computed for each subset of the trials by dividing the absolute power in each frequency band by the total power in all frequency bands. Splitting the trials allowed us to conduct an exploratory analysis and identify differences in power between the HSP and non-HSP groups on the first trials subset, as well as confirming and detailing these differences in the second one.

Statistical analyses

All statistical analyses were conducted using the SPSS (Version 22.0; IBM Corp., 2013). For the questionnaire data, mean scores were calculated for the HSP, introversion, and neuroticism scales. Correlations were calculated between the mean HSP scores and the mean introversion and neuroticism scores.

The same analyses were repeated for the 20 participants selected for the EEG recording. In addition, an independent samples t-test was performed in order to assess whether the two groups (HSP and non-HSP) had a significant difference in mean HSP scores. Analysis of variance (ANOVA) with group (HSP/non-HSP) as grouping variable, electrode site as between-subjects factor, and power as dependent variable was computed for each frequency band, both for the absolute and the relative power for the first subset of the trials.

For the second subset of the trials, the electrode

with the highest power in each frequency band was selected as follows: Fp1 for delta, Cz for theta, PO4 for alpha, and O1 for beta. Subsequently, four regions, one corresponding to each electrode were defined, and those electrodes from the same region which showed power similar to the highest one in each frequency band were grouped together and averaged separately for the absolute and relative power in the respective frequency bands. The regions and groupings were as follows: frontal (Fp1 and Fp2), fronto-central (Fz and Cz), parieto-occipital (PO3, PO4, O1, and O2), and occipital (O1, Oz, and O2). In order to test whether there is a significant difference in the distribution of different frequency bands in different regions, for each frequency band the average power was computed both for the region where the electrode with the highest power was identified and for each of the other three regions identified for the other three frequency bands. A three-way ANOVA, with a 2 (group: HSP/non-HSP) \times 4 (frequency: delta, theta, alpha, beta) \times 4 (region: frontal, fronto-central, parieto-occipital, occipital) design, and power value as dependent variable was run once for the absolute power, and once for the relative power. Pairwise comparisons with Bonferroni correction for multiple comparisons were conducted to follow up significant main effects and interactions.

Results

Questionnaires

Mean HSP scores across all 60 participants ranged between 2.78 and 6.33 ($M = 4.37$, $SD = .78$), mean introversion scores ranged from 1 to 7 ($M = 3.74$, $SD = 1.35$), and mean neuroticism scores ranged from 1.67 to 6.33 ($M = 3.68$, $SD = 1.36$). For the questionnaire data, the correlations between mean HSP score and mean introversion, and mean neuroticism scores, respectively, were significant ($r = .325$, $p = .011$, and $r = .505$, $p < .001$). Finally, for the sample selected for the EEG recording, the correlation between mean HSP score and mean neuroticism score was also significant ($r = .757$, $p < .001$), while the correlations between mean HSP score and mean introversion was nonsignificant ($r = .393$, $p = .087$).

The independent samples t-test revealed that the two groups differed significantly in the mean HSP score ($M_{HSP} = 5.55$, $SD_{HSP} = 0.41$, $M_{non-HSP} = 3.37$, $SD_{non-HSP} = 0.36$, $t(18) = 12.61$, $p < .001$). In addition, all participants in the HSP group had mean scores above 5, and all participants in the non-HSP group had mean scores below 4.

EEG data

Analysis on the first subset of the dataset. ANOVA revealed a significant effect of group for the absolute power in each of the four frequency bands ($F_{delta}(1, 575) = 47.64$, partial $\eta^2_{delta} = 0.08$, $F_{theta}(1, 575) = 70.28$, partial $\eta^2_{theta} = 0.11$, $F_{alpha}(1, 575) = 11.71$, partial $\eta^2_{alpha} = 0.02$, $F_{beta}(1, 575) = 73.46$, partial $\eta^2_{beta} = 0.11$, all $ps < .001$), and a significant effect of group on the relative power in the delta and alpha bands ($F_{delta}(1, 575) = 15.15$, partial $\eta^2_{delta} = 0.03$, $F_{alpha}(1, 575) = 19.95$, partial $\eta^2_{alpha} = 0.03$, all $ps < .001$).

For both absolute and relative power, no significant Group \times Electrode interaction was revealed (absolute: $F_{delta}(31, 575) = 0.077$, $F_{theta}(31, 575) = 0.399$, $F_{alpha}(31, 575) = 0.331$, $F_{beta}(31, 75) = 0.162$; relative: $F_{delta}(31, 575) = 0.099$, $F_{theta}(31, 575) = 0.193$, $F_{alpha}(31, 575) = 0.133$, $F_{beta}(31, 575) = 0.180$; all $ps > .05$). There was also no significant effect of group on the relative power in the theta and beta frequency ranges ($F_{theta}(1, 575) = 0.706$, $F_{beta}(1, 575) = 2.32$, all $ps > .05$).

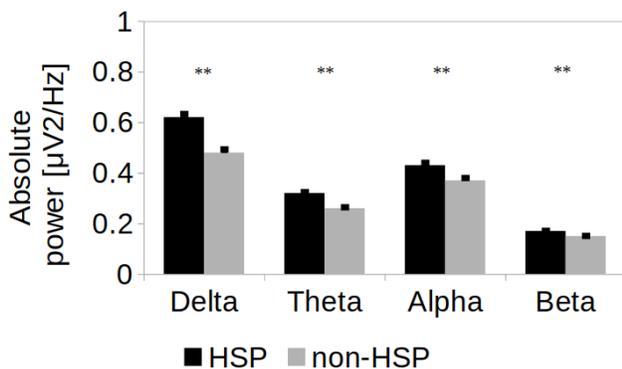


Figure 1. Mean absolute power ($\mu V^2/Hz$) and standard error of the mean for each of the four frequency bands (delta, theta, alpha, beta), plotted for HSP (in black) and non-HSP (in gray) groups.

Pairwise comparisons with Bonferroni correction for multiple comparisons were made between the

HSP and non-HSP group for all frequency bands in which there was a significant effect of group. Figure 1 shows the results obtained from the analysis of the absolute power. Pairwise comparisons between the two groups revealed that absolute power was significantly higher in the HSP group compared to the non-HSP group for each of the four frequency bands (delta: $M_{HSP} = 0.62$, $SEM_{HSP} = 0.014$, $M_{non-HSP} = 0.48$, $SEM_{non-HSP} = 0.014$, theta: $M_{HSP} = 0.32$, $SEM_{HSP} = 0.005$, $M_{non-HSP} = 0.26$, $SEM_{non-HSP} = 0.005$, alpha: $M_{HSP} = 0.43$, $SEM_{HSP} = 0.011$, $M_{non-HSP} = 0.37$, $SEM_{non-HSP} = 0.011$, beta: $M_{HSP} = 0.17$, $SEM_{HSP} = 0.002$, $M_{non-HSP} = 0.15$, $SEM_{non-HSP} = 0.002$, all $ps < .001$).

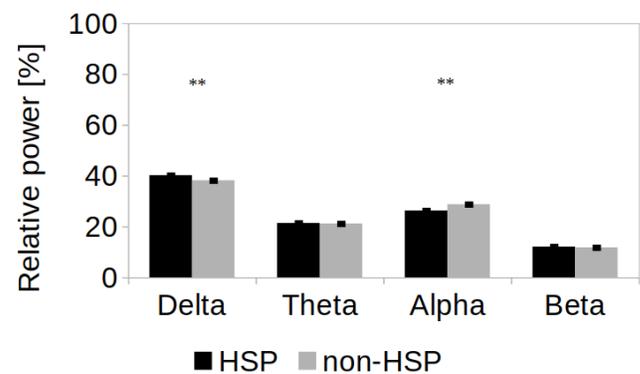


Figure 2. Mean relative power (%) and standard error of the mean for each of the four frequency bands (delta, theta, alpha, beta), plotted for HSP (in black) and non-HSP (in gray) groups.

Figure 2 shows the results obtained from the analysis of the relative power. Pairwise comparisons between the two groups showed that the relative power in the delta band was significantly higher in the HSP compared to the non-HSP group ($M_{HSP} = 40.2$, $SEM_{HSP} = 0.004$, $M_{non-HSP} = 38.2$, $SEM_{non-HSP} = 0.004$, $p < .001$), while the relative power in the alpha band was significantly lower in the HSP compared to the non-HSP group ($M_{HSP} = 26.3$, $SEM_{HSP} = 0.004$, $M_{non-HSP} = 28.8$, $SEM_{non-HSP} = 0.002$, $p < .001$). There were no significant differences between the two groups in the relative theta ($M_{HSP} = 21.4$, $SEM_{HSP} = 0.002$, $M_{non-HSP} = 21.2$, $SEM_{non-HSP} = 0.002$, $p > .05$) and beta power ($M_{HSP} = 12.1$, $SEM_{HSP} = 0.002$, $M_{non-HSP} = 11.8$, $SEM_{non-HSP} = 0.002$, $p > .05$). The electrode with the highest power for the delta frequency band was identified in the frontal region (electrode Fp1), for the theta band in the central region (electrode Cz), for the alpha band in the parieto-occipital region

(electrode PO4), and for the beta band in the occipital region (electrode O1).

Analysis on the second subset of the dataset. The results of the three-way ANOVA on the absolute power revealed significant main effects of group ($F(1, 288) = 11.149, p = .001, \text{partial } \eta^2 = .037$), frequency ($F(3, 288) = 94.5, p < .001, \text{partial } \eta^2 = .496$), and region ($F(3, 288) = 3.79, p = .011, \text{partial } \eta^2 = .038$), and a significant Region x Frequency interaction effect ($F(9, 288) = 6.38, p < .001, \text{partial } \eta^2 = .166$). Group x Frequency ($F(3, 288) = 1.83, p = .142$), Group x Region ($F(3, 288) = .067, p = .977$), and Group x Frequency x Region ($F(9, 288) = .041, p > .999$) interactions were not significant. Pairwise comparisons for group showed that the HSP group had a higher mean absolute power ($M = 0.437, SEM = .014$) than the non-HSP group ($M = 0.370, SEM = 0.014$).

Frequency was highest in the delta band ($M = 0.630, SEM = 0.020$), followed by alpha ($M = 0.483, SEM = 0.020$), theta ($M = 0.328, SEM = 0.020$), and beta ($M = 0.174, SEM = 0.020$). Absolute power was higher in the parieto-occipital ($M = 0.437, SEM = 0.020, p = .044$) and occipital ($M = 0.436, SEM = 0.020, p = .049$) regions compared to the fronto-central region. All other region comparisons were non-significant. The Region x Frequency interaction further showed that power in the delta band was higher for the frontal region ($M = 0.760, SEM = 0.040$) than for the frontocentral ($M = 0.581, SEM = 0.040, p = .011$), parieto-occipital ($M = 0.587, SEM = 0.040, p = .016$), and occipital ($M = 0.590, SEM = 0.040, p = .019$) regions, while power in the alpha band was higher in the parieto-occipital ($M = 0.635, SEM = 0.040$) and in the occipital ($M = 0.623, SEM = 0.040$) regions compared to the frontal ($M = 0.314, SEM = 0.040$) and fronto-central ($M = 0.360, SEM = 0.040$) regions (each $p < .001$, respectively). All other comparisons were non-significant.

In the three-way ANOVA on the relative power, no significant effects of group, region, or a group by region interaction was expected since relative power across all frequency bands always adds up to 100%. There was a significant effect of frequency ($F(3, 288) = 382, p < .001, \text{partial } \eta^2 = .799$), as well as significant

interactions of Group x Frequency ($F(3, 288) = 3.63, p = .013, \text{partial } \eta^2 = .036$) and Region x Frequency ($F(9, 288) = 24.54, p < .001, \text{partial } \eta^2 = .434$). No significant three-way interaction was found. Pairwise comparisons for frequency revealed the same relation as for the absolute power: delta ($M = 0.391, SEM = 0.006$) higher than alpha ($M = 0.290, SEM = 0.006$) higher than theta ($M = 0.208, SEM = 0.006$) higher than beta ($M = 0.112, SEM = 0.006$), all $ps < .001$. The same effects as for the absolute power were also obtained for the Region x Frequency interaction, with higher power in the delta band for the frontal region ($M = 0.489, SEM = 0.012$) than for the fronto-central ($M = 0.400, SEM = 0.012$), parieto-occipital ($M = 0.338, SEM = 0.012$), and occipital ($M = 0.338, SEM = 0.012$) regions (all $ps < .001$), while power in the alpha band was higher in the parieto-occipital ($M = 0.352, SEM = 0.012$) and in the occipital ($M = 0.351, SEM = 0.012$) regions compared to the frontal ($M = 0.209, SEM = 0.012$) and fronto-central ($M = 0.247, SEM = 0.012$) regions (all $ps < .001$). In addition, there was a trend for higher theta in the fronto-central region ($M = 0.239, SEM = 0.012$) compared to the parieto-occipital ($M = 0.195, SEM = 0.012, p = .072$) and occipital ($M = 0.196, SEM = 0.012, p = .082$) regions. Interestingly, the interaction Group x Frequency revealed higher relative delta power in the HSP ($M = 0.404, SEM = 0.009$) compared to the non-HSP group ($M = 0.378, SEM = 0.009, p = .033$), and lower relative alpha power in the HSP ($M = 0.275, SEM = 0.009$) compared to the non-HSP group ($M = 0.305, SEM = 0.009, p = .013$).

Discussion

Mean HSP scores as well as correlations between them, mean introversion and neuroticism scores were consistent with the ones reported in previous literature (Aron & Aron, 1997). Nevertheless, it is worth mentioning that very few participants had SPS scores in the lower tercile (below three). This effect might be partially explained by convenient sampling.

The results of the EEG frequency spectrum analysis on the first subset of the dataset revealed that HSP had higher absolute power in the delta, theta, alpha, and beta frequency bands, compared to people with low SPS scores. From a physiological

point of view, the spectral power measured in EEG reflects activity of the dendrites of cortical pyramidal cells, which are arranged in parallel and averaged under the surface of an electrode (Nunez, Wingeier, & Silberstein, 2001). Consequently, for the present study one could speculate that higher absolute power in HSP is associated with higher activity of the cortical pyramidal cells.

This would be in line with the hypothesis that SPS reflects a "pause-to-check" strategy, and that it imposes high metabolic costs on the brain (Wolf et al., 2008). This group effect was confirmed in the analysis conducted on the second subset of the dataset. The purpose of the second analysis was to also identify more specific differences between the two groups based on frequency and region. However, the lack of any significant interaction between group and frequency, or group and region, as well as group, region, and frequency could be taken as an indication that differences in absolute power between the two groups are present at the full brain scale and are not restricted to specific regions. Consequently, one theory could be that although excluded electrodes did not show very high power in different frequency bands, they contributed to the overall hypothesized effect of increased activity of the cortical pyramidal cells. Furthermore, the idea that increased neural activity is generalized could be linked to the observation that HSP show sensitivity to a wide variety of stimuli (Acevedo et al., 2014; Jagiellowicz et al., 2011).

The relative power analysis examined the contribution of each frequency band to the total power in the EEG spectrum. In the first half of the analysis we observed that for high HSP there was a higher relative power in the delta band, and a lower relative power in the alpha band. This result was further confirmed in the second half of the analysis by the significant group and frequency interaction. Studies on attention propose the existence of two dissociative brain networks, one involved in directing attention to external stimuli, and one involved in directing attention to internal stimuli. From a functional perspective, delta waves and increases in delta power, as well as decrease in alpha power, have been associated with a directed focus towards

internal representations, i.e., internalized attention (Aftanas & Golocheikine, 2001; Harmony, 2013). In the context of resting state EEG and SPS, it could therefore be argued that when asked to relax HSP are better at shifting their attentional focus from possible distractors in the external environment to their internal state. Again, this is consistent with the increased processing depth in SPS. Further studies could be conducted in order to examine the difference in delta increase and alpha decrease between HSP and non-HSP during tasks that require either internally or externally directed concentration.

Differences in delta and alpha power during rest might also be the result of neuroplastic changes associated with repeated concentration on internal processes in order to suppress external, overexciting stimuli in HSP. Support for this interpretation comes from studies on meditation showing that in rest, even when they are not actively meditating, meditation practitioners have higher delta activity in parts of the prefrontal cortex and anterior cingulate cortex compared to non-meditators (Faber et al., 2008; Tei et al., 2009).

Theta and beta band activity have been linked to cognitive processing during mental tasks (Asada, Fukuda, Tsunoda, Yamaguchi, & Tonoike 1999; Engel & Fries, 2010), and therefore the absence of a significant difference in relative power between the HSP and non-HSP groups in these two bands could be a consequence of the fact that the participants did not perform any demanding cognitive task during the resting period.

There was also a significant difference among power in the four frequency bands, both for absolute and relative power, with the delta band showing the highest power followed by alpha, theta, and beta. The fact that the highest power was obtained for the delta and alpha frequency bands regardless of group could indicate that participants were in a relaxed state and tried to focus their attention internally, while reducing attention to the external environment (Aftanas & Golocheikine, 2001; Harmony, 2013). Yet, as mentioned above, HSP participants were better able to control the focus of their attention. The selected electrodes for each of the four frequency bands belong to regions consistent with previous

reports which have the distribution of these frequency bands over the scalp in the context of the default mode network of the human brain (Chen, Feng, Zhao, Yin, & Wang, 2008). However, the more detailed analysis conducted for the second data subset revealed a significantly different distribution by region only for the delta and alpha power, with delta distributed more over the frontal region, and alpha more towards the parieto-occipital and occipital regions. In addition, there was a trend for higher relative theta power over the frontocentral region. Nevertheless, Chen et al. (2008) separately analyzed low frequency beta (13–23 Hz), and high frequency beta (23–30 Hz), and found that they were distributed over the occipital, and prefrontal regions, respectively, while the current study combined the two. This might explain why there was no significant region difference in beta distribution.

Similarly, although usually reported over the frontal midline (Aftanas & Golocheikine, 2001; Chen et al., 2008), the theta rhythm is present in other regions as well and it is particularly increased over the occipital region during decreased vigilance (Beatty, Greenberg, Deibler, & O'Hanlon, 1974).

Two limitations of the current study should be noted. First, there were no participants in the lower tercile of the absolute HSP score distribution. It is probable that the effect shown in the current study would be stronger with extremes being compared. Second, there was only one male in the high SPS group, possibly because men tend to report lower SPS scores (Aron & Aron, 1997). Although gender is not expected to influence in any way the frequency spectrum power composition, further studies should be conducted in which to control for a potential influence of these factors.

In conclusion, the present study shows that HSP and non-HSP exhibit different spectral patterns in resting state EEG activity, which might be linked to the fact that HSP are better able to focus their attention on their internal state when needed. Moreover, this effect does not appear to be restricted to a single brain region but seems to be generalized. The study thus represents the first step in the endeavour to elucidate the intricate neural correlates accountable for differences in SPS and lays the

foundation for future investigations into the topic. However, further studies are necessary for a more in-depth analysis of the link between SPS and EEG spectral power, particularly in task performance, and provide more conclusive evidence in this area.

Contribution Statement

CD, BG, and MS designed the study. CD collected and analyzed the data. CD wrote the manuscript under the supervision of BG and MS. All authors discussed the results and contributed to the final manuscript.

Conflicts of Interest

The authors declare no competing interests in publishing this article.

References

- Acevedo, B. P., Aron, E. N., Aron, A., Sangster, M. D., Collins, N., & Brown, L. L. (2014). The highly sensitive brain: An fMRI study of sensory processing sensitivity and response to others' emotions. *Brain and Behavior, 4*(4), 580–594. <https://doi.org/10.1002/brb3.242>
- Aftanas, L. I., & Golocheikine, S. A. (2001). Human anterior and frontal midline theta and lower alpha reflect emotionally positive state and internalized attention: High-resolution EEG investigation of meditation. *Neuroscience Letters, 310*(1), 57–60. [https://doi.org/10.1016/s0304-3940\(01\)02094-8](https://doi.org/10.1016/s0304-3940(01)02094-8)
- Alhaddad, M. J., Kamel, M., Malibary, H., Thabit, K., Dahlwi, F., & Hadi, A. (2012). P300 speller efficiency with common average reference. *Lecture Notes in Computer Science, 234*–241. https://doi.org/10.1007/978-3-642-31368-4_28
- Aron, E. N., & Aron, A. (1997). Sensory-processing sensitivity and its relation to introversion and emotionality. *Journal of Personality and Social Psychology, 73*(2), 345–368. <https://doi.org/10.1037/0022-3514.73.2.345>
- Aron, E. N., Aron, A., & Jagiellowicz, J. (2012). Sensory processing sensitivity: A review in the light of the evolution of biological responsiveness. *Personality and Social Psychology Review, 16*(3), 262–282. <https://doi.org/10.1177/1088868311434213>
- Aron, A., Ketay, S., Hedden, T., Aron, E. N., Rose Markus, H., & Gabrieli, J. D. E. (2010). Temperament trait of sensory processing sensitivity moderates cultural differences in neural response. *Social Cognitive and Affective Neuroscience, 5*(2-3), 219–226. <https://doi.org/10.1093/scan/nsq028>
- Asada, H., Fukuda, Y., Tsunoda, S., Yamaguchi, M., & Tonoike, M. (1999). Frontal midline theta rhythms reflect alternative activation of prefrontal cortex and anterior cingulate cortex in humans. *Neuroscience Letters, 274*(1), 29–32. [https://doi.org/10.1016/s0304-3940\(99\)00679-5](https://doi.org/10.1016/s0304-3940(99)00679-5)
- Beatty, J., Greenberg, A., Deibler, W. P., & O'Hanlon, J. F. (1974). Operant control of occipital theta rhythm affects performance in a radar monitoring task. *Science, 183*(4127), 871–873. <https://doi.org/10.1126/science.183.4127.871>
- Carver, C. S., & White, T. L. (1994). Behavioral inhibition, behavioral

- activation, and affective responses to impending reward and punishment: The BIS/BAS Scales. *Journal of Personality and Social Psychology*, *67*(2), 319–333. <https://doi.org/10.1037/0022-3514.67.2.319>
- Chen, A. C. N., Feng, W., Zhao, H., Yin, Y., & Wang, P. (2008).** EEG default mode network in the human brain: Spectral regional field powers. *NeuroImage*, *41*(2), 561–574. <https://doi.org/10.1016/j.neuroimage.2007.12.064>
- Chen, C., Xiu, D., Chen, C., Moyzis, R., Xia, M., He, Y., ... & Wang, Y. (2015).** Regional homogeneity of resting-state brain activity suppresses the effect of dopamine-related genes on sensory processing sensitivity. *PLoS one*, *10*(8), e0133143. <https://doi.org/10.1371/journal.pone.0133143>
- Corbetta, M., & Shulman, G. L. (2002).** Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*(3), 215–229. <https://doi.org/10.1038/nrn755>
- Delorme, A., & Makeig, S. (2004).** EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*, 9–21. <https://doi.org/10.1016/j.jneumeth.2003.10.009>
- Engel, A. K., & Fries, P. (2010).** Beta-band oscillations—signalling the status quo? *Current Opinion in Neurobiology*, *20*(2), 156–165. <https://doi.org/10.1016/j.conb.2010.02.015>
- Faber, P. L., Steiner, M. E., Lehmann, D., Pascual-Marqui, R. D., Jancke, L., Esslen, M., & Gianotti, L. R. R. (2008).** Deactivation of the medial prefrontal cortex in experienced Zen meditators. *Brain Topography*, *20*, 172. <https://doi.org/10.1007/s10548-007-0042-1>
- Goldman, R. I., Stern, J. M., Engel Jr, J., & Cohen, M. S. (2002).** Simultaneous EEG and fMRI of the alpha rhythm. *Neuroreport*, *13*(18), 2487. <https://doi.org/10.1097/01.wnr.0000047685.08940.d0>
- Hagemann, D., Naumann, E., Lürken, A., Becker, G., Maier, S., & Bartussek, D. (1999).** EEG asymmetry, dispositional mood and personality. *Personality and Individual Differences*, *27*(3), 541–568. [http://doi.org/10.1016/S0191-8869\(98\)00263-3](http://doi.org/10.1016/S0191-8869(98)00263-3)
- Harmony, T. (2013).** The functional significance of delta oscillations in cognitive processing. *Frontiers in Integrative Neuroscience*, *7*. <https://doi.org/10.3389/fnint.2013.00083>
- Hopfinger, J. B., & Mangun, G. R. (1998).** Reflexive attention modulates processing of visual stimuli in human extrastriate cortex. *Psychological Science*, *9*(6), 441–447. <https://doi.org/10.1111/1467-9280.00083>
- IBM Corp. (2013).** *IBM SPSS Statistics for Windows, Version 22.0*. Armonk, NY: IBM Corp.
- Jann, K., Kottlow, M., Dierks, T., Boesch, C., & Koenig, T. (2010).** Topographic electrophysiological signatures of fMRI resting state networks. *PLoS one*, *5*(9), e12945. <https://doi.org/10.1371/journal.pone.0012945>
- Knyazev, G. G. (2012).** EEG delta oscillations as a correlate of basic homeostatic and motivational processes. *Neuroscience & Biobehavioral Reviews*, *36*(1), 677–695. <https://doi.org/10.1016/j.neubiorev.2011.10.002>
- Laufs, H., Krakow, K., Sterzer, P., Eger, E., Beyerle, A., Salek-Haddadi, A., & Kleinschmidt, A. (2003).** Electroencephalographic signatures of attentional and cognitive default modes in spontaneous brain activity fluctuations at rest. *Proceedings of the National Academy of Sciences*, *100*(19), 11053–11058. <https://doi.org/10.1073/pnas.1831638100>
- Lewicki, P., & Czyniewska, M. (2001).** Styles of nonconscious intelligence. In Proceedings of the AISB'01 Symposium on Nonconscious Intelligence: From Natural to Artificial (Vol. 21, pp. 43–50).
- Jagiellowicz, J., Xu, X., Aron, A., Aron, E., Cao, G., Feng, T., & Weng, X. (2011).** The trait of sensory processing sensitivity and neural responses to changes in visual scenes. *Social Cognitive and Affective Neuroscience*, *6*(1), 38–47. doi.org/10.1093/scan/nsq001
- MATLAB (2014).** *version 8.3.0.532 (R2014a)*, Natick, Massachusetts: The MathWorks, Inc.
- Nunez, P. L., Wingeier, B. M., & Silberstein, R. B. (2001).** Spatial-temporal structures of human alpha rhythms: Theory, microcurrent sources, multiscale measurements, and global binding of local networks. *Human Brain Mapping*, *13*(3), 125–164. <https://doi.org/10.1002/hbm.1030>
- Oppenheim, A. V., Schaffer, R. W., & Buck, R. J. Discrete-time signal processing.** Upper Saddle River, NJ: Prentice Hall, 1999, p. 488.
- Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989).** Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology*, *72*(2), 184–187. [https://doi.org/10.1016/0013-4694\(89\)90180-6](https://doi.org/10.1016/0013-4694(89)90180-6)
- Tei, S., Faber, P. L., Lehmann, D., Tsujiuchi, T., Kumano, H., Pascual-Marqui, R. D., ... & Kochi, K. (2009).** Meditators and non-meditators: EEG source imaging during resting. *Brain Topography*, *22*(3), 158–165. <https://doi.org/10.1007/s10548-009-0107-4>
- Tse, P. U. (2005).** Voluntary attention modulates the brightness of overlapping transparent surfaces. *Vision Research*, *45*(9), 1095–1098. <https://doi.org/10.1016/j.visres.2004.11.001>
- Wolf, M., van Doorn, G. S., & Weissing, F. J. (2008).** Evolutionary emergence of responsive and unresponsive personalities. *Proceedings of the National Academy of Sciences*, *105*(41), 15825–15830. <https://doi.org/10.1073/pnas.0805473105>