

Effects of a randomised trial of 5-week heart rate variability biofeedback intervention on  
mind wandering and associated brain function

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## **Abstract**

Previous research suggests that excessive negative self-related thought during mind wandering involves the default mode network (DMN) core subsystem and the orbitofrontal cortex (OFC). Heart rate variability (HRV) biofeedback, which involves slow paced breathing to increase HRV, is known to promote emotional well-being. However, it remains unclear whether it has positive effects on mind wandering and associated brain function. We conducted a study where young adults were randomly assigned to one of two 5-week interventions involving daily biofeedback that either increased heart rate oscillations via slow paced breathing (Osc+ condition) or had little effect on heart rate oscillations (active control or Osc- condition). The two intervention conditions did not differentially affect mind wandering and DMN core-OFC functional connectivity. However, the magnitude of participants' heart rate oscillations during daily biofeedback practice was associated with pre-to-post decreases in mind wandering and in DMN core-OFC functional connectivity. Furthermore, the reduction in the DMN core-OFC connectivity was associated with a decrease in mind wandering. Our results suggested that daily sessions involving high amplitude heart rate oscillations may help reduce negative mind wandering and associated brain function.

## **Introduction**

Mind wandering involves generating thoughts unrelated to the present situation. While it is not inherently detrimental (Konjedi & Maleeh, 2017; Poerio et al., 2013) and can be beneficial in some situations (e.g., creative thinking, problem solving and constructive positive daydreaming; Baird et al., 2012; Gable et al., 2019; McMillan et al., 2013), emotional consequences of mind wandering tend to be more negative than positive. In one study (Killingsworth & Gilbert, 2010), 2250 adults of various ages, occupations and nationalities answered the following questions about their daily activities via a web application: “How are you feeling right now?”, “What are you doing right now?”, and “Are you thinking about something other than what you’re currently doing?” The results revealed that mind wandering occurred in 46.9% of their samples and that people reported being less happy when their minds were wandering than when they were not.

During mind wandering, people often experience thoughts and feelings about themselves and their life (D’Argembeau, 2018). The default mode network (DMN) is a brain network involved in both mind wandering and self-related thoughts (Christoff et al., 2009; Mason et al., 2007). Although the DMN was originally regarded as a unitary system, more recent research suggested that the DMN can be divided into three functionally independent subsystems, namely the core, medial temporal lobe, and dorsal medial prefrontal cortex subsystems (Andrews-Hanna, 2012; Andrews-Hanna et al., 2010; Andrews-Hanna et al., 2014). The core subsystem, which consists of anterior medial prefrontal cortex (mPFC) and posterior cingulate cortex (PCC), is particularly important for self-referential processing (Andrews-Hanna, 2012; Andrews-Hanna et al., 2010) and is also implicated in rumination and depression (Burkhouse et al., 2017; Cooney et al., 2010; Zhou et al., 2020). In depressed patients, self-generated thoughts were more negative,

less positive, more self-related and more past-related, relative to healthy controls (Hoffmann et al., 2016). Another key region associated with depression and other psychological disorders is the orbitofrontal cortex (OFC; Cooney et al., 2010; Drevets, 2007; Rolls, 2019; Rolls et al., 2020), which is involved in emotion-related learning and decision-making, rewards, punishments, and emotional and behavioral flexibility (O'Doherty et al., 2001; Rempel-Clower, 2007; Rolls, 2004, 2019). Functional and structural alterations in the OFC occur in many psychiatric disorders including anxiety disorders, major depression, posttraumatic stress disorder, obsessive-compulsive disorder, schizophrenia, bipolar and personality disorders (Jackowski et al., 2012; Milad & Rauch, 2007; Thorsen et al., 2018). Importantly, previous studies found that depression increased resting state functional connectivity between the lateral OFC and the PCC/precuneus (part of the DMN core subsystem; Cheng et al., 2018). Another study (Koelsch et al., 2022) found that functional connectivity between the PCC and the medial OFC plays a role in negative spontaneous nonintentional thoughts (or negative mind wandering). Although the relationship between DMN-OFC hyperconnectivity and mind wandering is a relatively new area of investigation, previous studies together suggest that the interaction between the DMN core subsystem and the OFC may play a key role in excessive negative self-related thought during mind wandering.

Meditation can help reduce episodes of mind wandering and promote emotional well-being (Brandmeyer & Delorme, 2018; Mrazek et al., 2013; Rodriguez-Larios et al., 2021; van Agteren et al., 2021). Meditation can also decrease activity in the primary regions of the DMN (the mPFC and PCC/precuneus) during meditation relative to resting state (Brewer et al., 2011), during meditation relative to an active cognitive task (Garrison et al., 2015) and during present-centered self-focus vs. narrative self-focus (Farb et al., 2007). Some meditative practices not

only improve psychological health but also have a positive impact on physiological well-being, such as slowing down breathing and increasing heart rate variability (HRV; Bernardi et al., 2001; Lehrer et al., 1999; Peng et al., 2004; Peng et al., 1999; Phongsuphap et al., 2008). During these meditative practices, breathing slows down and drives large heart rate oscillations at the breathing frequency (Bernardi et al., 2001; Lehrer et al., 1999; Peng et al., 2004). Prior research suggests that slow paced breathing practices alone (without explicit meditation training) can improve emotional well-being. Using an HRV biofeedback procedure, participants can be trained to breathe at their resonance frequency which is around 0.1 Hz or 10 seconds per breath (Lehrer et al., 2013). During paced breathing at their own baroreflex resonance frequency, people can significantly increase acute levels of HRV. Repeated daily practice over several weeks promote long term emotional health benefits (for review see (Lehrer & Gevirtz, 2014)). Recent meta analyses (Lehrer et al., 2020; Pizzoli et al., 2021) also suggested that HRV biofeedback improves symptoms of various types of psychological disorders, such as depression and anxiety, in both clinical and non-clinical populations. Consistent with these prior emotion-related effects, our recent randomized clinical trial (for preprint see Nashiro et al., 2021) demonstrated that a 5-week intervention involving daily biofeedback aimed at increasing heart rate oscillations significantly increased resting-state functional connectivity in emotion-related networks whereas it did not have a significant impact on functional connectivity in the overall DMN.

It remains unclear whether the HRV biofeedback has positive effects on mind wandering and associated brain function. To address these questions, we used the data from our previous study where 106 healthy younger adults were randomly assigned to one of two 5-week interventions involving daily biofeedback that either increased heart rate oscillations (Osc+) or had little effect on heart rate oscillations (Osc-). We formulated this question after initiating our

trial and so added a measure of mind wandering after the study started; about half of the participants completed the measure ( $N = 55$ ). We tested the hypotheses that the Osc+ intervention would reduce the tendency for mind wandering and decrease functional connectivity between the DMN core subsystem and the OFC, relative to the Osc- intervention.

## **Methods**

### ***Participants***

We recruited 121 participants aged between 18 and 35 years through a USC online bulletin board, the USC Healthy Minds community subject pool, Facebook and flyers. Participants signed informed consent approved by the University of Southern California (USC) Institutional Review Board. Prospective participants were screened and excluded for major medical, neurological, or psychiatric illnesses. We also excluded people who had a disorder that would impede performing the HRV biofeedback procedures (e.g., coronary artery disease, angina, cardiac pacemaker), who currently trained in relaxation, biofeedback or breathing techniques, or were on any psychoactive drugs other than antidepressants or anti-anxiety medications. We included people who were taking antidepressant or anti-anxiety medication and/or attending psychotherapy only if the treatment had been ongoing and unchanged for at least three months and no changes were anticipated. Eligible participants were assigned to small groups of 3-6 people, and each group met at the same time and day each week except for the weeks when they underwent MRI. After recruitment and scheduling of each wave of groups were complete, we randomly assigned groups to a condition using flipping a coin method. Hence, each participant was randomly assigned to one condition involving daily biofeedback aimed at increasing heart rate oscillations (Osc+) or decreasing heart rate oscillations (Osc-). Upon completing the study, participants were paid for their participation and received bonus

payments based on their individual and group performances (see ‘rewards for performance’ in Supplementary Materials for more details). Out of 121 participants, 106 completed the interventions, and 100 completed the resting state scan both before and after the intervention. Two participants (one person from each condition) were excluded due to unsuccessful denoising pipeline results. Additionally, two Osc+ participants who did not follow the instructions were excluded from the analyses (a pre-defined exclusion criterion). During the post-intervention resting state scan, these two participants breathed slowly as if they were engaged in the Osc+ biofeedback (i.e., they failed to follow the instructions, which were to simply rest while looking at the white cross at the center of the screen and breathing normally). The remaining 96 participants were included in the resting state analyses (Supplemental Figure 1 and Supplementary Table 1). For the analyses involving heart rate data, three participants in the Osc- condition were excluded because we failed to save heart rate data from ear sensors due to technical issues with the first version of the Osc- biofeedback software, leaving 93 out of 96 participants in the analyses. For the analyses involving behavioral data (i.e., the mind wandering score detailed in the ‘behavioral assessments’ section), we used data from a subset of 55 participants since the measure was added after initiation of the study protocol.

### ***Overview of 7-week protocol schedule***

A full description of the study has been detailed in a preprint (Nashiro et al., 2021). Briefly, the study protocol involved seven weekly lab visits and five weeks of home biofeedback training. The first lab visit involved the non-MRI baseline measurements, including emotion questionnaires. The second lab visit involved baseline MRI assessments followed by the first biofeedback training session. Between the second and seventh lab visits (approximately five weeks), participants were instructed to engage in daily biofeedback practice 20-40 minutes/day

and visit the lab weekly. The sixth lab visit repeated the emotion questionnaires from the first lab visit. The seventh lab visit repeated the baseline MRI assessments.

### ***Biofeedback training***

***Osc+ condition.*** In the second lab visit, Osc+ participants tried out several breathing paces around 10s/breath to see which induced the largest oscillations in their heart rate (their own resonance frequency; Lehrer et al., 2013) using the emWave Pro software (Heartmath, 2016). Participants were asked to wear an ear sensor to measure their pulse and to breathe in and out with a visual pacer. They were instructed to inhale through the nose when the blue bar went up, and to exhale through the mouth when the blue bar went down (e.g., 5s inhale/5s exhale for 10s/breath cycle). They were asked to breathe at 5 different paces (9s, 10s, 11s, 12s, and 13s per breath, which approximately corresponds with 6.5, 6, 5.5, 5, and 4.5 breaths per minute as in Lehrer et al. (2013) for 5 minutes each. To identify each participant's best approximate resonance frequency, researchers evaluated various aspects of the oscillatory dynamics for each breathing pace using Kubios HRV Premium 3.1 software (Tarvainen et al., 2014) and assessed which one had the most of the following characteristics: highest low frequency (LF) power, the highest maximum LF amplitude peak on the spectral graph, highest peak-to-trough amplitude, cleanest and highest-amplitude LF peak, highest coherence score and highest root mean square of successive differences (RMSSD).

To complete home training, participants received an ear sensor and a small laptop with the emWave Pro software. During their daily training sessions, participants breathed to a pacer set to their resonance frequency determined in their prior lab visit. They received biofeedback on their heart rate oscillatory activity via a real-time plot of their heart rate and a 'coherence' score, which is a built-in metric score provided by the emWave Pro software. Coherence is



characterized by a sine-wave-like pattern in the HRV waveform in the LF range (McCraty et al., 2009). Thus, a higher coherence score is reflected in the HRV power spectrum as a large increase in power in the LF band around 0.1 Hz. Participants were instructed to aim for a high coherence score. The coherence score was calculated as  $\text{peak power}/(\text{total power} - \text{peak power})$ . Peak power was identified by finding the highest peak within the range of 0.04 – 0.26 Hz and calculating the integral of the window 0.015 Hz above and below this highest peak. Total power was computed for the 0.0033 – 0.4 Hz range.

In the third week, participants returned to the lab to receive coaching from researchers who checked again which breathing frequency produced the strongest heart rate oscillations (i.e., resonance frequency). Participants were asked to breathe at 3 different paces for 5 minutes each: the best pace from the prior week's visit, a one second per breath shorter, and a one second per breath longer than their best pace (e.g., if their best pace in the prior week was 13s, they tried 12s, 13s and 14s per breath). As in the second week, researchers evaluated the same aforementioned characteristics of these 3 paces and assigned the participant the one that best approximated their resonance frequency for home training that week. In subsequent weekly visits, during 5-min training segments, participants were asked to try out abdominal breathing with pursed lips as well as other strategies of their choice to enhance coherence in a relaxed manner (Lehrer et al., 2013). Their assigned breathing paces ranged from 9-14s/breath. The mean was 11.16s (SD = 1.49) and the median was 11s.

***Osc- condition.*** An ideal comparison to this Osc+ condition would be another condition with similar biofeedback information, participant expectations and time spent training but no increases in heart rate oscillatory activity during the training sessions. Thus, we designed a decrease-oscillations comparison condition (Osc-) in which participants received heart rate

biofeedback aimed at reducing their heart rate oscillations while breathing normally. In addition, to try to avoid having them discover that they could reduce HRV simply by increasing physical activity (Sarmiento et al., 2013), we instructed them to also try to decrease their heart rate during the training sessions.

In the second lab visit, participants were asked to come up with five strategies to lower heart rate and heart rate oscillations (e.g., imaging the ocean, listening to nature sounds, listening to instrumental music, thinking of their loved ones, occasionally closing eyes). Participants were asked to wear the same biofeedback ear sensor as Osc+ participants and view real-time heart rate biofeedback while they tried each strategy for 5 minutes. Researchers analyzed the data using Kubios HRV Premium 3.1 software and identified the best strategy as the one that exhibited the opposite characteristics from the Osc+ condition: lowest LF power, the minimum LF amplitude peak on the spectral graph, lowest peak-to- trough amplitude, multiple and lowest-amplitude LF peak, highest calmness score (see below for more details) and lowest RMSSD.

To complete home training, participants received an ear sensor and a small laptop with a custom software. During their daily training sessions, participants aimed at reducing heart rate and heart rate oscillations using the best strategy determined in their prior lab visit. In contrast with the Osc+ group, the custom-developed software provided a ‘calmness’ score, which was calculated by multiplying the coherence score that would have been displayed in the Osc+ condition by -1 and adding 10 (i.e., an ‘anti-coherence’ score). The net result was that participants got more positive feedback and higher calmness scores when their heart rate oscillatory activity in the 0.04 – 0.26 Hz range was low (see ‘Osc- condition’ in Supplementary Materials for more details).

In the third lab visit, participants were asked to select three strategies and try them out for 5 minutes each. The strategy identified as best (based on the aforementioned characteristics) was selected as the one to focus on during home training sessions the following week. In subsequent weekly visits, during 5-min training segments, participants were again asked to try out strategies of their choice.

### ***Brain imaging data acquisition and preprocessing***

We employed a 3T Siemens MAGNETOM Trio scanner with a 32-channel head array coil at the USC Dana and David Dornsife Neuroimaging Center. T1-weighted 3D structural MRI brain scans were acquired pre and post intervention using a magnetization prepared rapid acquisition gradient echo (MPRAGE) sequence with TR = 2300 ms, TE = 2.26 ms, slice thickness = 1.0 mm, flip angle = 9°, field of view = 256 mm, and voxel size = 1.0 x 1.0 x 1.0 mm, with 175 volumes collected (4:44 min). Resting state functional MRI was acquired using multi-echo-planar imaging sequence with TR= 2400 mm, TE 18/35/53 ms, slice thickness = 3.0 mm, flip angle = 75°, field of view = 240 mm, voxel size = 3.0 x 3.0 x 3.0 mm, 175 volumes and acquisition time = 7 min. During the resting state scan, participants were instructed to rest, breathe normally and look at the central white cross on the black screen.

To minimize the effects of motion and physiological effects, we used multi-echo sequences during our fMRI scans. Previous research suggests that Blood Oxygen Level Dependent (BOLD) T2\* signal is linearly dependent on echo time, whereas non-BOLD signal is not echo-time dependent (Kundu et al., 2012). Multi-echo acquisitions allow uncoupling of BOLD signal from movement artifact and significantly improve accuracy of functional connectivity analyses (Dipasquale et al., 2017). Thus, we implemented a denoising pipeline using independent components analysis (ICA) and echo-time dependence to distinguish BOLD

fluctuations from non-BOLD artifacts including motion and physiology (Kundu et al., 2013). In addition, the six motion parameters and signal from white matter and cerebrospinal fluid were removed from each participant's preprocessed data. We applied a band-pass filter of 0.01-0.1Hz and used FSL FLIRT to linearly align the denoised data to each participant's brain-extracted structural image and the standard MNI 2-mm brain.

### ***Heart rate data acquisition and preprocessing***

Kubios HRV Premium 3.1 was used to compute autoregressive spectral power for each training session over the course of 5 weeks. We averaged the autoregressive total spectral power from all training sessions for each participant. We extracted the summed power within the 0.063~0.125 Hz range for each participant (corresponding with 8-16s, a range encompassing breathing paces used by Osc+ participants) to obtain a measure of resonance frequency oscillatory activity during biofeedback. Before conducting statistical analyses, we log transformed the power values.

### ***Behavioral assessments***

At pre- and post-intervention lab visits (the first and sixth visits), a subset of 55 participants completed the 20-item version of the Five Facet Mindfulness Questionnaire (FFMQ). The FFMQ consisted of five subscales: acting with awareness, observing, describing, nonjudging of inner experience and nonreacting of inner experience. In this study, we were particularly interested in the acting with awareness subscale, which measures the tendency to get distracted from the present-moment experience by mind wandering. Items for this subscale include, "when I do things, my mind wanders off and I'm easily distracted," "I don't pay attention to what I'm doing because I'm daydreaming, worrying, or otherwise distracted," "I'm easily distracted," and "I find it difficult to stay focused on what's happening in the present."

Participants responded to each item using a 5-point scale (1= Never/rarely true and 5 = Very often/always true). Previous research found that the acting with awareness subscale is associated with spontaneous mind wandering (Seli et al., 2015) and the frequency of mind wandering episodes in daily life (Ottaviani & Couyoumdjian, 2013). The items in the acting with awareness subscale is usually reverse scored; however, for the ease of the readers, we used the non-reversed scores with higher scores indicating greater tendency for mind wandering (hereinafter called ‘the mind wandering score’).

### *Analyses*

***Brain data analysis.*** We used the DMN core subsystem and OFC masks defined in a prior study (Thomas Yeo et al., 2011). We performed a FSL dual-regression analysis using the DMN core mask as the ROI, which created subject-specific time series for the DMN core regions. The resulting individual time series were used to create subject-specific spatial maps of the DMN core ROI. From the subject-specific z-transformed maps, we extracted mean functional connectivity values from the OFC, which represent functional connectivity strengths between the DMN core regions and OFC. We calculated the difference between pre and post functional connectivity values by subtracting pre values from post values. We conducted independent t-tests to examine whether the Osc+ and Osc- conditions differ in pre-post changes in functional connectivity. The difference score was also used in correlation analyses.

***HRV data analysis.*** For each participant, we calculated the average heart rate oscillation power within the resonance frequency range of 0.063~0.125 Hz during home training across the 5-week training period (hereinafter called ‘training oscillation power’), which was used as the training performance index in the analyses. We performed an independent t-test to examine

whether the two conditions differ in training oscillation power. The training oscillation power was also used in correlation analyses.

***Behavioral data analysis.*** We summed the four items in the acting with awareness subscale (i.e., the mind wandering score). Higher scores indicate greater tendency for mind wandering. We then computed the difference between pre and post mind wandering scores by subtracting pre values from post values. We performed an independent t-test to examine whether the two conditions differ in pre-post changes in the mind wandering score. The difference score was also used in correlation analyses.

## **Results**

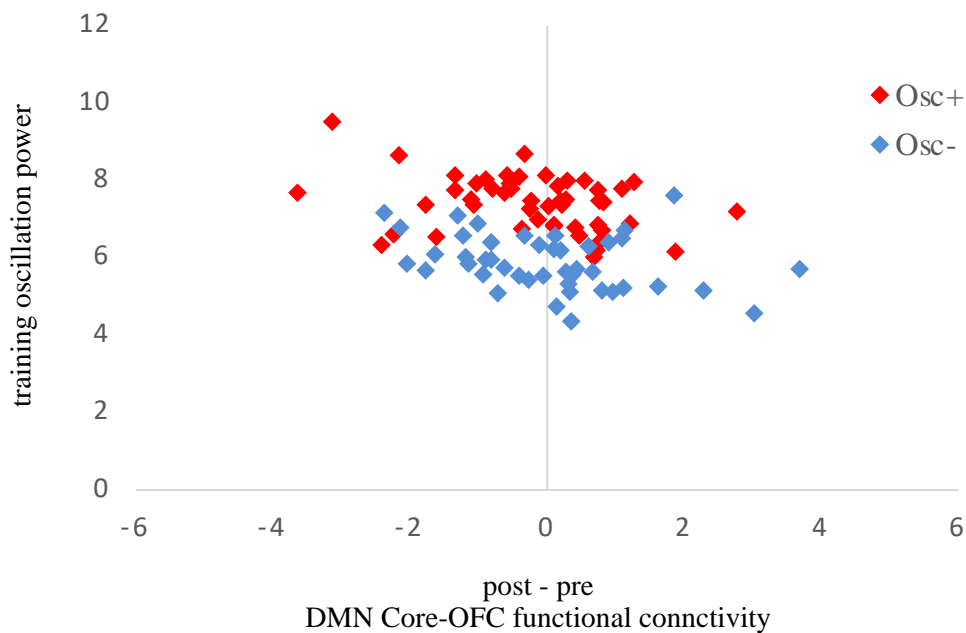
As a manipulation check, we examined whether the participants in the two conditions differed in training oscillation power. Consistent with our prior report with a larger sample size (for preprint see; (Nashiro et al., 2021), there was a significant condition difference in training oscillation power (see Supplemental Table 2 for the values). We also report condition differences in other HRV indices during training and baseline in Supplemental Table 2.

We examined whether the two conditions differ in pre-to-post changes in functional connectivity between the DMN core subsystem and the OFC (Core-OFC). There was no significant condition difference,  $t(94) = -1.12$ ,  $p = .264$ ,  $r = .114$  (Supplementary Fig. 2). We also examined whether the two conditions differ in pre-to-post changes in mind wandering, but no significant difference was found,  $t(53) = -0.45$ ,  $p = .654$ ,  $r = .061$  (Supplementary Fig. 3). Additionally, we performed 2 (timepoint: pre vs. post) x 2 (condition: Osc+ vs. Osc-) ANOVAs for Core-OFC functional connectivity and mind wandering; however, no significant results were found (Supplementary Fig. 4).

Next, we examined whether training oscillation power (i.e., training performance index) was associated with pre-to-post changes in functional connectivity across all participants in both conditions. There was a significant negative correlation between training oscillation power and pre-post change in Core-OFC connectivity,  $r(91) = -.299$ ,  $p = .004$ ,  $CI[-.474, -.102]$  (Figure 1), such that higher training oscillation power was associated with a greater reduction in Core-OFC functional connectivity. Separate analyses for each condition also showed a significant negative correlation between training oscillation power and pre-post change in Core-OFC connectivity for the Osc+ condition,  $r(47) = -.343$ ,  $p = .016$ ,  $CI[-.570, -.069]$ , and for the Osc- condition,  $r(42) = -.330$ ,  $p = .029$ ,  $CI[-.571, -.037]$ .

### Figure 1

*Correlation between training oscillation power and pre-post change in DMN Core-OFC functional connectivity*



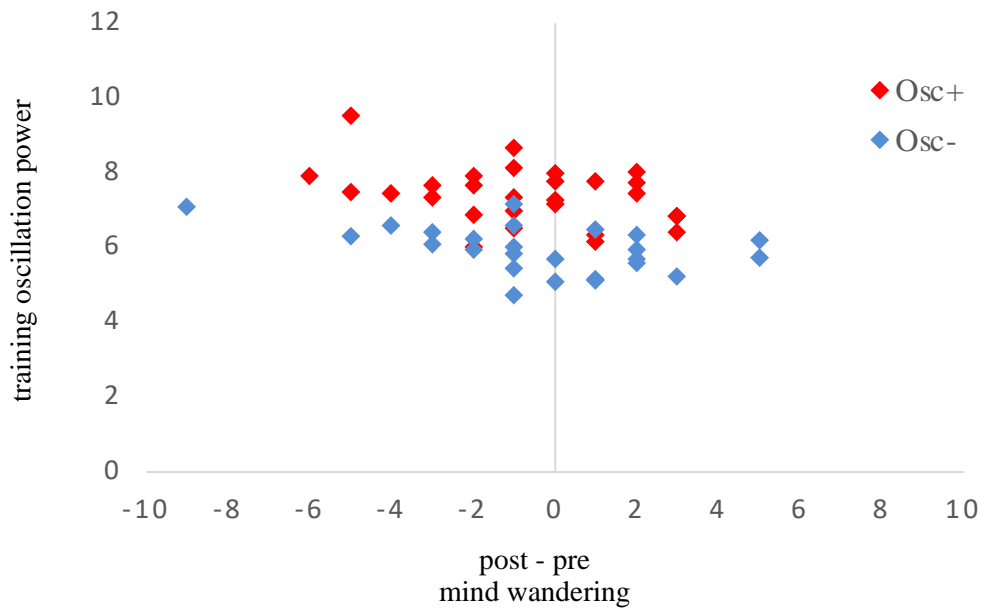
*Note.* Greater training oscillation power was associated with a greater reduction in DMN Core-OFC functional connectivity across both conditions. When we removed two people whose standard deviation was greater than 2.5 for post-pre Core-OFC connectivity, the correlation remained significant,  $r(89) = -.269$ ,  $p = .010$ ,  $CI[-.450, -.066]$ .

There was a negative correlation between training oscillation power and pre-post change in mind wandering scores,  $r(51) = -.322$ ,  $p = .019$ ,  $CI[-.545, -.056]$  (Figure 2), suggesting that higher training oscillation power was associated with a greater reduction in mind wandering. The confidence interval (CI) indicates that the correlation could be as small as  $-.056$  which would not be very meaningful to as high as  $-.545$  which would be quite meaningful. Our data are consistent with either of these interpretations and a larger sample size would increase the precision (decrease the CI). In addition, a greater reduction in mind wandering was associated with a greater decrease in Core-OFC connectivity,  $r(51) = .304$ ,  $p = .027$ ,  $CI[.037, .531]$  (Figure 3). The CI indicates that the correlation could be as small as  $.037$  which would not be very meaningful to as high as  $.531$  which would be quite meaningful.

## **Figure 2**

*Correlation between training oscillation power and pre-post change in mind wandering*

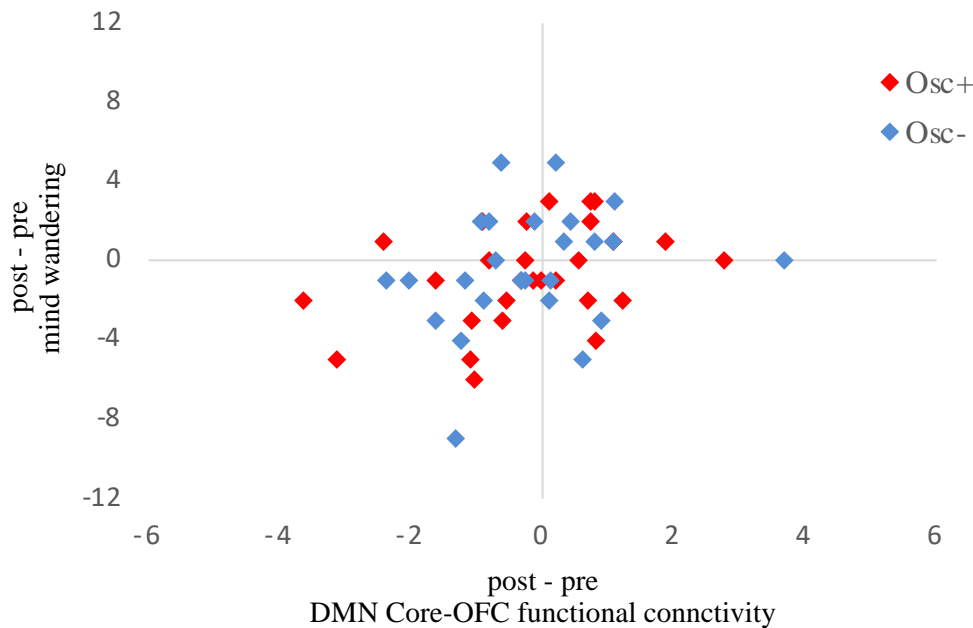




*Note.* Greater training oscillation power was associated with a greater reduction in mind wandering across both conditions. When we removed one person whose standard deviation was greater than 2.5 for post-pre mind wandering score, the correlation remained significant,  $r(50) = -.331, p = .016, CI[-.554, -.064]$ .

**Figure 3**

*Correlation between pre-post change in mind wandering and that in DMN Core-OFC functional connectivity*



*Note.* A greater reduction in mind wandering was associated with a greater decrease in DMN Core-OFC functional connectivity across both conditions.

## Discussion

The two interventions did not significantly differ in pre-post changes in Core-OFC functional connectivity and mind wandering. However, higher training oscillation power (i.e., how large participants' heart rate oscillations were during daily training) was associated with decreases in Core-OFC functional connectivity and mind wandering. Furthermore, reduced Core-OFC connectivity was associated with a decrease in mind wandering.

Previous research suggests that greater Core-OFC functional connectivity is associated with excessive negative self-related thought during mind wandering. Our results suggested that daily sessions involving high amplitude heart rate oscillations may help reduce both Core-OFC functional connectivity and mind wandering beyond the session time itself. The current findings also provide some insights into a possible link between HRV, DMN and mind wandering. In the

neurovisceral integration model (Thayer & Lane, 2000, 2009), it was proposed that HRV reflects the activity of an integrative neural network regulating physiological, emotional and cognitive responses. In this model, the prefrontal cortex (including the mPFC that is part of the DMN core subsystem) exerts inhibitory control over subcortical regions. Higher resting HRV reflects more effective prefrontal cortex ability to inhibit subcortical circuits (Thayer & Lane, 2000, 2009) and thus, is associated with better emotion regulation (Williams et al., 2015). However, HRV may go beyond signaling the functioning of regulatory brain regions - that is, inducing high HRV may improve the brain's capacity to regulate emotion (Mather & Thayer, 2018). In fact, our recent randomized clinical trial (for preprint see Nashiro et al., 2021) including the participants in the present study demonstrated that daily sessions inducing high heart rate oscillations significantly increased resting-state functional connectivity within emotion-related networks involving a wide range of emotional and autonomic processes. Together with our current findings, it seems plausible that inducing large heart rate oscillations increases brain's regulatory activity while decreasing brain's maladaptive activity (e.g., DMN Core-OFC hyperconnectivity). Such alterations of emotion-related brain networks may contribute to improving emotional well-being by diminishing negative mind wandering.

As discussed earlier, meditation also helps reduce mind wandering (Brandmeyer & Delorme, 2018; Mrazek et al., 2013; Rodriguez-Larios et al., 2021) and DMN activation (Brewer et al., 2011; Farb et al., 2007; Garrison et al., 2015). Some meditative practices also slow down breathing and increase heart rate variability (Bernardi et al., 2001; Lehrer et al., 1999; Peng et al., 1999; Phongsuphap et al., 2008). Thus, these physiological changes (i.e., slow breathing and large heart rate oscillations) are commonly seen during some meditative practices and HRV biofeedback training, both of which are known to improve emotional well-being (Goyal et al.,

2014; Khoury et al., 2017; Lehrer et al., 2020; Pizzoli et al., 2021). Although the underlying mechanism is still unclear, physiological changes during meditation may contribute to emotional well-being. It is possible that meditative practices that incorporate high amplitude heart rate oscillations may be more effective in reducing mind wandering and associated brain function than meditations that do not integrate such physiological changes.

Some limitations should be noted. There is some debate in the literature about how to conceptualize mind wandering. There are several definitions of mind wandering, such as task-unrelated thought, stimulus-independent thought, and spontaneous vs. deliberate thought (Christoff et al., 2016; Seli et al., 2018; Smallwood & Schooler, 2015). Some researchers argue that mind wandering is a heterogeneous construct with multiple facets instead of a unitary construct (Seli et al., 2018). In this study, we used the acting of awareness subscale as a measure of mind wandering in everyday life. Thus, it is possible that we failed to capture specific aspects of mind wandering, such as task-related vs. task-unrelated thought (Smallwood & Schooler, 2015) and spontaneous vs. deliberate mind wandering (Seli et al., 2015). An important area of future research is to investigate how different domains of mind wandering may be influenced by high amplitude of heart rate oscillations. Another limitation of this study is that only a subset of participants completed the mind wandering questionnaire since it was added after initiation of the study protocol. Future studies should replicate the current findings with a larger sample size in order to increase the precision of a confidence interval (Amrhein et al., 2019) although it is also important to note that a low sample size in the current study cannot lead to a spurious significant effect (Zuckerman et al., 1993). It would also be worthwhile for future research to further investigate neural mechanisms linking HRV and mind wandering. In addition, future studies should investigate common and separate neural mechanisms underlying heart rate

oscillation intervention and meditation practices and how they jointly or separately promote emotional well-being (e.g., testing whether attention to the breath during meditation practices vs. Osc+ training leads to similar or different neural patterns and behavioral outcomes; Weng et al., 2020). It is also important to replicate the current findings in clinical populations including individuals with depression and anxiety disorders.

### **Open Practices Statement**

Data supporting the findings of this study will be made publicly available at OpenNeuro. None of the present analyses were preregistered; however, the original study was preregistered (ClinicalTrials.gov NCT03458910; Heart Rate Variability and Emotion Regulation or “HRV-ER”).

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**Conflict of interest**

The authors declare no competing interests.

## Supplementary Materials

### Osc- condition

As described in the main test, we wanted to avoid having Osc- participants figure out that one way to reduce their HRV and get positive feedback would be to do something like get up and do jumping jacks (physical activity typically decreases HRV (Sarmiento et al., 2013)). Thus, we instructed them to try to reduce their heart rate in addition to lowering their heart rate oscillations and we intended to build into the feedback a minor point penalty when heart rate was the highest it had been in a short while. However, due to a coding error not detected until the study was completed, this point adjustment did the opposite, giving a penalty when heart rate was the lowest it had been in the most recent 15 s. More specifically, every 5 s, a local maximum interbeat interval (IBI) was set based on the maximum IBI from the past 15 s. At that point, if the participant's current IBI was longer than this local maximum, the calmness score displayed for the next 5 s was the anti-coherence score - 2. Naturally, current IBI was usually lower than the local maximum, and in those cases, the calmness score was the anti-coherence score +1. Thus, there was a penalty in their calmness score for moments when their heart rate was slower than it had been in any of the past 15 s. As reported in Supplementary Table 2, average heart rate during biofeedback sessions did not differ significantly across conditions. Therefore, this additional feedback appeared to have had little impact on heart rate, which is consistent with prior findings that biofeedback to increase or decrease heart rate has no significant impact (Bennett et al., 1978).

### Rewards for performance

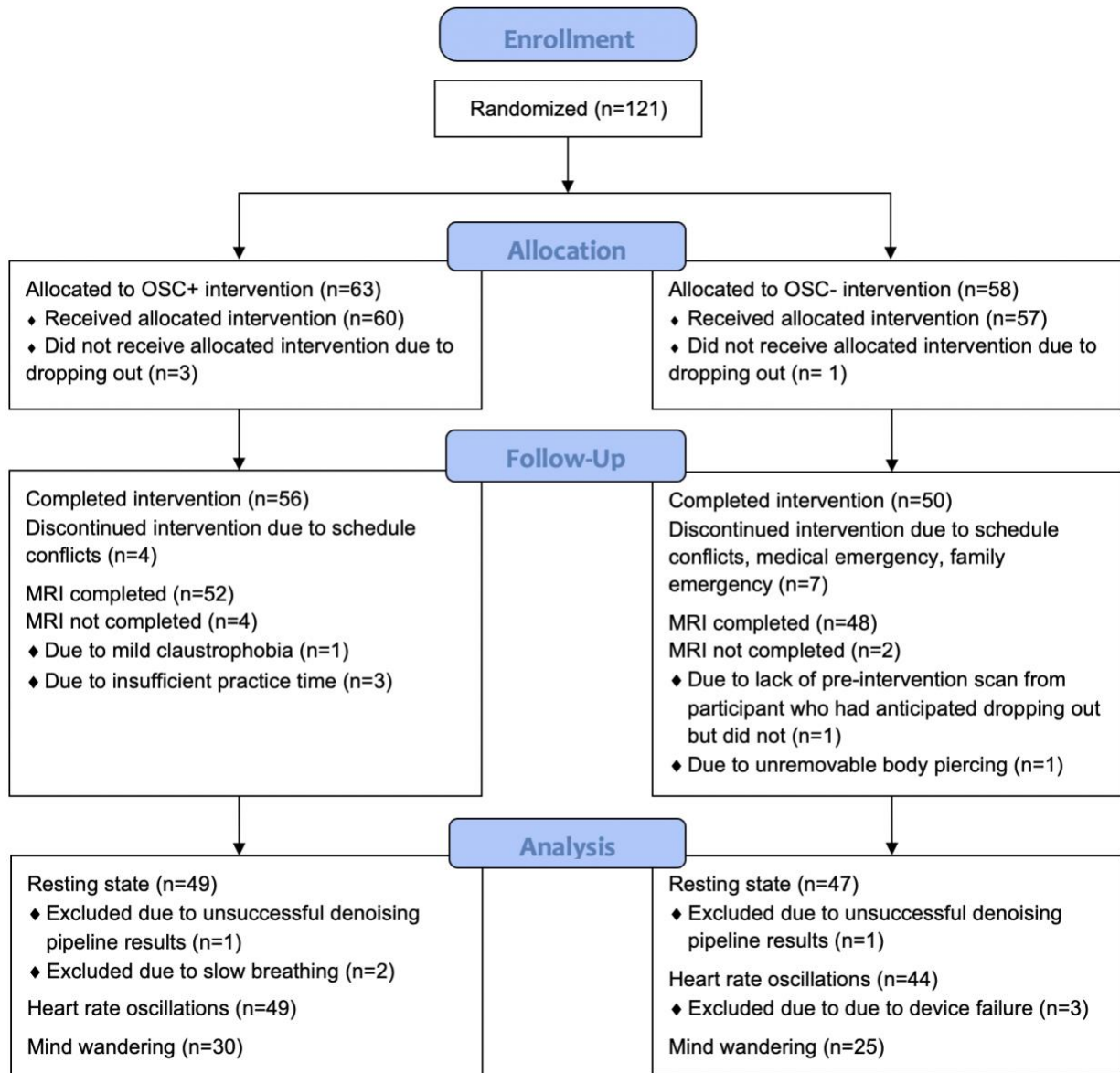
In addition to receiving compensation of \$15 per hour for each lab visit, participants were eligible to receive rewards based on individual and group performance. For individual

performance rewards, each week participants had the opportunity to earn \$2 for each instance (up to a maximum of 10) they exceeded their assigned target score (target scores were assigned each week, and were the average of the top 10 scores earned from the previous week's training sessions plus 0.3). Group performance rewards were earned when members of a participant's group completed a minimum of 80% of their assigned biofeedback training minutes. For example, if a participant completed 100% of their training, they received an additional \$3 for each group member who also completed 100% of their training. If a participant completed 80% of their training, they received an additional \$2 for each group member who also completed at least 80% of their training. Rewards were calculated weekly, and participants received weekly updates on their earnings at their lab visit.

# Supplementary Figure 1

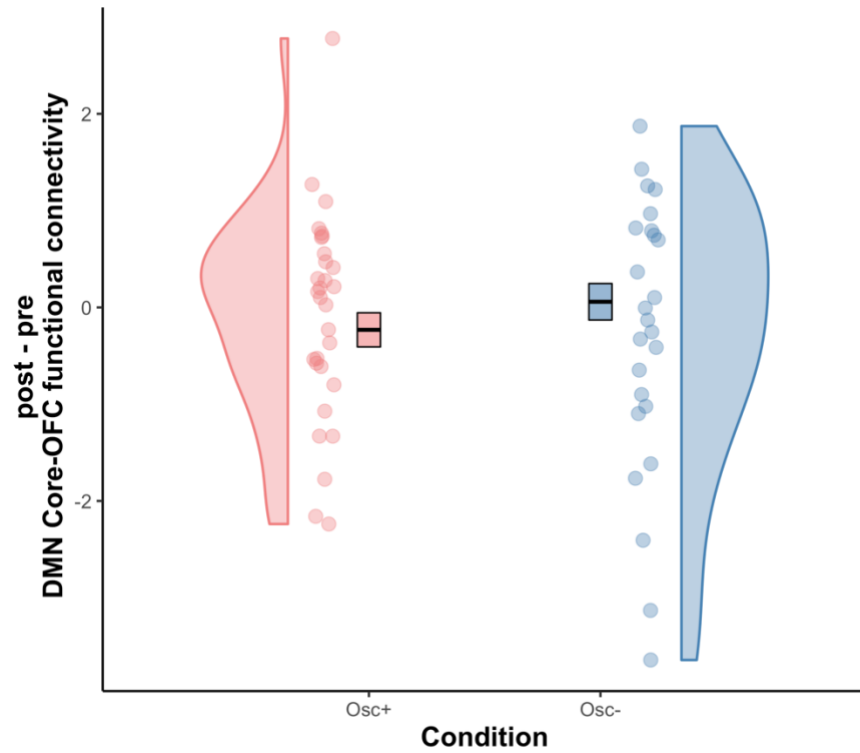
## CONSORT Flow Diagram

### CONSORT 2010 Flow Diagram



## Supplementary Figure 2

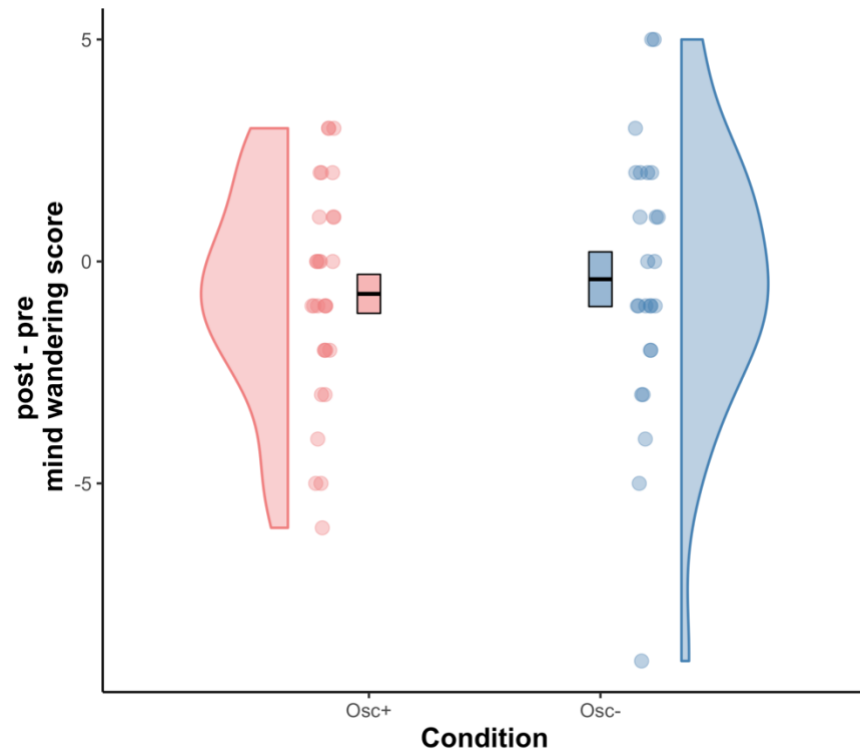
*Pre-post changes in functional connectivity between DMN core subsystem and the OFC in the two intervention conditions*



*Note.* There was no significant condition difference in pre-post changes in functional connectivity between the DMN core subsystem and the OFC.

### Supplementary Figure 3.

*Pre-post changes in mind wandering in the two intervention conditions*

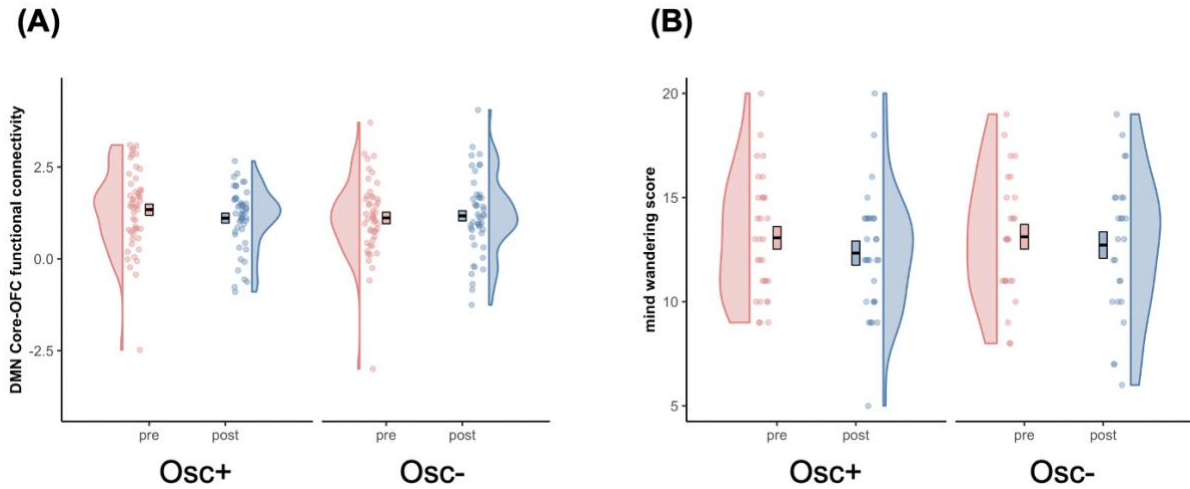


*Note.* There was no significant condition difference in pre-post changes in the mind wandering score.



### Supplementary Figure 4.

Results of repeated measure ANOVAs (A) for DMN core-OFC functional connectivity and (B) for mind wandering



(A) For DMN core-OFC functional connectivity, there was no significant main effect of time,  $F(1, 94) = 0.45, p = .503, \eta_p^2 = .005$ , and no significant interaction between time and condition,  $F(1, 94) = 1.26, p = .264, \eta_p^2 = .013$ . (B) For mind wandering, there was no significant main effect of time,  $F(1, 53) = 2.35, p = .132, \eta_p^2 = .042$ , and no significant interaction between time and condition,  $F(1, 53) = 0.20, p = .654, \eta_p^2 = .004$ .

## Supplementary Table S1

*Age, gender and education across intervention conditions*

	Osc+ (n = 49)	Osc- (n = 47)	Group difference
Age (years)	22.84 ± 2.47	22.72 ± 3.20	<i>p</i> = .85
Gender (F/M)	23/26	24/23	<i>p</i> = .69
Education (years)	16.07 ± 1.79	15.85 ± 2.60	<i>p</i> = .63

*Note.* Osc+ = increase-oscillations; Osc- = decrease-oscillations

## Supplementary Table S2

### *Baseline and training HRV across intervention conditions*

Time	Index	Osc+ (N=49)		Osc- (n=44)		Group difference p value
		Mean	SD	Mean	SD	
Baseline	mean HR	72.45	10.30	72.58	9.33	.95
	RMSSD	68.24	40.31	56.94	21.07	.10
	log LF-power (0.04~0.15 Hz)	7.19	1.04	6.92	0.95	.18
	log HF-power (0.15~0.4 Hz)	6.93	1.08	6.80	0.76	.51
	log Total-power	7.95	1.00	7.74	0.76	.26
Training	mean heart rate	76.47	6.76	75.15	8.17	.40
	RMSSD	78.73	31.56	75.13	29.10	.57
	log LF-power (0.04~0.15 Hz)	8.60	0.69	7.10	0.62	<.001
	log HF-power (0.15~0.4 Hz)	6.85	0.87	7.05	0.70	.22
	total power	8.88	0.68	7.91	0.63	<.001
	coherence	3.34	1.03	1.00	0.17	<.001
	training oscillation power (0.063~0.125 Hz)	7.42	0.72	5.88	0.71	<.001

*Note.* There was a significant condition difference in training oscillation power, which is consistent with our prior report with a larger sample size (for preprint see; (Nashiro et al., 2021)).