Is Meditation always relaxing? Investigating Heart Rate, Heart Rate Variability, Experienced Effort and Likeability during Training of three types of Meditation

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Is meditation always relaxing? Investigating heart rate, heart rate variability, experienced effort and likeability during training of three types of meditation

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ABSTRACT

Meditation is often associated with a relaxed state of the body. However, meditation can also be regarded as a type of mental task and training, associated with mental effort and physiological arousal. The cardiovascular effects of meditation may vary depending on the type of meditation, degree of mental effort, and amount of training. In the current study we assessed heart rate (HR), high-frequency heart rate variability (HF-HRV) and subjective ratings of effort and likeability during three types of meditation varying in their cognitive and attentional requirements, namely breathing meditation, loving-kindness meditation and observing-thoughts meditation. In the context of the *ReSource* project, a one-year longitudinal mental training study, participants practiced each meditation exercise on a daily basis for 3 months. As expected HR and effort were higher during loving-kindness meditation and observing-thoughts meditation compared to breathing meditation. With training over time HR and likeability increased, while HF-HRV and the subjective experience of effort decreased. The increase in HR and decrease in HF-HRV over training was higher for loving-kindness meditation and observing-thoughts meditation compared to breathing meditation. In contrast to implicit beliefs that meditation is always relaxing and associated with low arousal, the current results show that core meditations aiming at improving compassion and meta-cognitive skills require effort and are associated with physiological arousal compared to breathing meditation. Overall these findings can be useful in making more specific suggestions about which type of meditation is most adaptive for a given context and population.

1. Introduction

It is widely assumed that meditation, irrespective of the type, is a way to relax by inducing a hypometabolic state of the body and a tranquil, but alert state of the mind (Benson et al., 1974; Jevning et al., 1992; Lazar et al., 2000). Recently, however, attention has been drawn to the fact that meditation might not generally lead to a relaxation response and that the effects of meditation on psychophysiological processes might depend on factors including meditation type and level of meditation experience (Britton et al., 2014). A better understanding about which types of meditation have relaxing or arousing effects will be crucial to make more precise suggestions about the applicability of meditation in different domains and populations. It is therefore important to empirically test whether different types of meditation have arousing or relaxing effects on psychological and physiological states and how these effects change with training expertise.

The current project focused on three meditation exercises including breathing-meditation, loving-kindness meditation and observing-thoughts meditation. These three meditation exercises can be regarded as the most widely practiced meditation exercises in Buddhist contemplative traditions (Wallace, 2006). The three core exercises differ with respect to the cognitive and affective processes involved, as well as with respect to the skills that they train. Breathing meditation requires the redirection and holding of attention to the object of breath and trains sustained attention and interoception (Malinowski, 2013). Loving-kindness meditation involves cognitive processes including redirection of attention to mental imagery and sentences, as well as remembering sentences, generating and maintaining mental imagery (Hofmann et al., 2011). Furthermore it involves affective processes such as generating and sustaining positive affect in order to train an increase in positive emotions, compassion and prosocial behavior. The observing-thoughts meditation requires cognitive processes such as redirection and holding attention to the object of thoughts, categorization of thoughts, development and maintaining meta-awareness in order to

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train detachment from mental events. Due to the greater amount and complexity of attentional, cognitive and affective processes involved in loving-kindness meditation and observing-thoughts meditation as compared to breathing meditation we assume that these exercises can be categorized as more demanding than breathing meditation and thus should be associated to higher levels of self-reported effort and physiological arousal when performed.

Meditation within Buddhist traditions can be regarded as a mental training technique that aims to train cognitive skills including sustained attention, working memory and other executive processes (Hölzel et al., 2011; Slagter et al., 2011; Wallace, 1999). It is suggested that meditation training is initially linked to mental effort, which should decrease with training expertise over time (Tang et al., 2012). Previous research has found that moderate practice of meditation improves measures of cognitive resources, including reduced mind wandering and increased attentional capacity (Lutz et al., 2009; Mrazek et al., 2013; Zeidan et al., 2010a). Perceived effort is also known to be related to feelings of enjoyment while one is profoundly focused on a task (Csikszentmihalyi, 2014). Evidence suggests that feelings of enjoyment are high if one's perceived ability to solve the task matches the capacities required to solve the task (Csikszentmihalyi and LeFevre, 1989). To our knowledge there are currently no studies that have directly assessed changes of perceived effort and enjoyment during meditation training over time. Based on studies showing that meditation can improve performance in cognitive tasks, we expect that effort during meditation will decrease over time while enjoyment will increase as participants become more experienced with the meditation training (Tang et al., 2012; Zanesco et al., 2013; Zeidan et al., 2010a).

Perceived mental effort is also often linked to physiological arousal (Hansen et al., 2003; Luft et al., 2009). Mental states that require high cognitive demands are known to influence the autonomic nervous system (ANS), divided into the parasympathetic nervous system (PNS) and sympathetic nervous system (SNS). Heart rate (HR) and heart rate variability (HRV) are often used as biomarkers of the ANS. HRV, in particular its high-frequency (HF-HRV) component (0.15 to 0.40 Hz), is a marker of the PNS activity (Camm et al., 1996; Reyes del Paso et al., 2013) and related to a variety of psychological factors including attention, working memory and emotion regulation (Thayer and Lane, 2009). We did not include the low-frequency (0.04 to 0.15 Hz) or vey-low frequency components ($\leq$0.04) as additional outcome measures because their interpretation as indicators of autonomic activity remains unclear (Billman, 2011). Instead we used HR as a marker of SNS activity, because HR acceleration is known to be caused by SNS activity through the release of norepinephrine (Camm et al., 1996). Increased HR is associated with cognitive arousal and mental effort (Critchley et al., 2013). Previous studies provide evidence that increased PNS activity is linked to improved cognitive control during the performance of cognitive tasks (Hansen et al., 2003; Overbeek et al., 2014). Based on the expected decrease in perceived mental effort over time and based on the evidence that cardiac activity is related to mental effort we predicted that HR during meditation will decrease, while HF-HRV will increase over training.

So far the majority of studies on the influence of meditation on HR and HF-HRV have investigated the difference between meditation state and baseline conditions (for reviews see (Kok et al., 2013; Olex et al., 2013)). Regarding the effects of meditation compared to baseline measures of cardiovascular activity many studies on the effects of attention-focused types of meditation show an increase in parasympathetic activity as assessed by increases in HF-HRV or decreases in HR (Krygier et al., 2013; Libby et al., 2012; Takahashi et al., 2005; Wu and Lo, 2008; Zeidan et al., 2010b). In contrast, Lutz and colleagues showed that compassion meditation in experts led to an increase in HR compared to a baseline condition suggesting an activation of the SNS during compassion meditation (Lutz et al., 2009). In a previous cross-sectional study with experienced meditators, Peng et al. showed that HR was higher during types of meditation with controlled breathing compared to a relaxation meditation without controlled breathing (Peng et al., 2004). In a more recent cross-sectional study with expert meditators from different Buddhist traditions, changes in HF-HRV varied across types of meditation: An increase in HF-HRV was found during Theravada types of meditation that included a concentrative focus on bodily sensations. In contrast, a decrease in HF-HRV was found during Vajrayana types of meditation that included an active generation of mental imagery (Amihai and Kozhevnikov, 2014). These findings suggest that effects of meditation on cardiovascular activity might vary as a function of the type of meditation and the degree of meditation experience of the participants. Thus, it is important to conduct longitudinal studies in meditation naive participants. In contrast to previous cross-sectional studies, a longitudinal design would allow for the study how the practices of different types of meditation influence cardiovascular activity over time. To our knowledge, however, there have been no studies comparing the influence of different types of meditation on training-induced changes over time in cardiac responses during meditation state from naive participants. Therefore, based on evidence that different types of meditation influence PNS and SNS activity differently, and based on expected changes with increased training expertise, we hypothesized that different types of meditation change cardiac activity and perceived effort and enjoyment differently over time.

The current project, which is part of a nine-month longitudinal mental training study called the *ReSource* project (Singer et al., in preparation), compared subjective and physiological signatures during breathing meditation, loving-kindness meditation and observing-thoughts meditation and how these change through training. Each meditation exercise was trained within a three-month training module on a daily basis at home while participants listened to guided audio-files with instructions given by qualified meditation teachers. For further details see Section 2.1, 2.2 and Singer et al. (in preparation). Measures of the present study included HF-HRV as a marker of PNS activity and HR as a marker of SNS activity, as well as ratings of subjective experiences of effort and likeability during breathing meditation, loving-kindness meditation and observing-thoughts meditation. The measures were taken in week 3 and week 13 within each training module. The analysis of the current study is based on a within-subject design with the factor time (week 3 and week 13) and the factor type of exercise (breathing meditation, loving-kindness meditation and observing-thoughts meditation). Initially all participants learned the breathing meditation, because it trained skills, which were required to learn the loving-kindness meditation and observing-thoughts meditation. The order of exercises was counterbalanced for loving-kindness meditation and observing-thoughts meditation.

We had the following specific hypotheses:

(1) Based on the differences with regard to the amount and complexity of cognitive and affective processes involved during each type of meditation, we hypothesized that the loving-kindness meditation and observing-thoughts meditation are more effortful compared to breathing meditation. Therefore we expected HR and effort to be higher and HF-HRV and likeability to be lower for loving-kindness meditation and observing-thoughts meditation as compared to breathing meditation.
(2) In line with studies on changes in skill acquisition through mental training over time, we predicted that HR and effort will decrease from week 3 to week 13, whereas HF-HRV and experienced likeability will increase from week 3 to week 13.
(3) Based on the first hypothesis that different types of meditation influence cardiac responses differently, we expected changes in HR, HF-HRV, effort and likeability over time to be different across the three core exercises. Due to the more demanding processes involved during loving-kindness meditation and observing-thoughts meditation, we expected the decrease in HR and effort and increase in HF-HRV and enjoyment to be smaller compared to breathing meditation.

2. Methods

2.1. Participants

The current sample was recruited for the *ReSource* project, a longitudinal mental training study conducted in the cities of Leipzig and Berlin from April 2013 to May 2014. A cohort of 80 healthy participants was recruited to undergo the training program in Leipzig and another cohort of 80 healthy participants was recruited to do the training in Berlin. Participants underwent several stages of screening before being admitted to the study and were only permitted to the study if they had no prior experience with intense meditation training. Details about the recruitment and screening procedure can be found in the *ReSource* handbook (Singer et al., in preparation). The total sample size of the current study was N = 156 (male: 63, female: 93) with a mean age of 41.17 (std. dev.: 9.34). The study has been approved by the Research Ethics Committee of the University of Leipzig (Ethik-Kommission an der Medizinischen Fakultät der Universität Leipzig) and the Research Ethics Committee of the Humboldt University in Berlin (Ethikkommission der Humboldt-Universität zu Berlin, Mathematisch-Naturwissenschaftliche Fakultät II, Institut für Psychologie). Participants were briefed about all experimental measures taken within the study and confirmed their agreement to undergo the experimental measurements by signing a consent form before the beginning of the project.

2.2. Procedure

In the current study participants learned three core exercises that were taught in three training modules that each lasted for 13 weeks. The breathing meditation was taught in the Presence Module, the loving-kindness meditation was taught in the Affective Module and the observing-thoughts meditation was taught in the Perspective Module. The order of the training modules differed for the two training cohorts. Training cohort 1 started with the Presence Module, continued with the Affective Module and finished with the Perspective Module. Training cohort 2 started with the Presence Module, continued with the Perspective Module and finished with the Affective Module. Throughout the study participants were instructed to learn the core exercises by qualified meditation teachers. Before the beginning of each training module participants went on a 3-day retreat with the meditation teachers in order to familiarize with the respective core exercise. During each training module, participants were asked to train the core exercise on a daily basis and to listen to a 20-minute guided audio file of the respective exercise at least 5 times per week. In order to start with the daily meditation exercise participants had to log in on a web-based training platform, which was designed for the *ReSource* project. Participants could access the platform both with a computer or cell phones that they were equipped with. Data of participants' training frequency were logged on the platform each time participants completed a meditation exercise. In addition to the daily meditation practice at home, participants were asked to attend a weekly 2 hour training session with the meditation teachers. Training sessions were offered in the morning (10 AM to 12 AM) or in the evening (7 PM to 9 PM). During the weekly training sessions, participants underwent the guided core exercise. In addition, participants learned practical information about how to integrate their meditation experiences into everyday-life and had the opportunity to ask questions about the exercises. Measurements of the current study were taken during the weekly training sessions in week 3 and in week 13 within each training module for both training cohorts in Berlin and Leipzig. In total 6 measurement time points were recorded for each training cohort. During each measurement time point a scientist or lab assistant joined the weekly meditation session in order to keep a time protocol of the start and the end time of the core exercise during the meditation sessions.

The guided meditations from the audio-files and the weekly training sessions were based on the following instructions.

2.2.1. Breathing meditation

During this meditation exercise, participants were asked to focus their attention on their in-breath and out-breath. In case participants lost the focus on the breath they were asked to refocus their attention on their breath. The overall goal of this practice was to increase sustained attention and increase interoceptive awareness.

2.2.2. Loving-kindness meditation

During this guided meditation exercise, participants were asked to set the intention to first wish themselves benevolent feelings by using repeating sentences such as “May you be happy”. Afterwards participants were asked to extend these beneficial wishes to family, friends, strangers, people they have difficulties with and finally all living beings. The overall goal of the loving-kindness meditation was to cultivate feelings of love, warmth and benevolence that are directed towards oneself or other people and increase positive emotions, compassion and prosocial behavior.

2.2.3. Observing-thoughts meditation

During the observing-thoughts meditation participants were asked to focus their attention on the coming and going of their own thoughts. In case participants lost the focus on their thoughts they were asked to refocus their attention back to their thoughts. The goal of this exercise was to familiarize with the dynamic nature of one's stream of thought and to learn to detach from thoughts and develop a meta-awareness. For more detailed information about the training protocol and the core exercises see Singer et al. (in preparation).

2.3. Measures

2.3.1. Subjective meditation state measures

During the weekly meditations, the degree of experienced effort and enjoyment was assessed after the completion of the core exercise for each measurement time point. Participants were asked to report how much effort they experienced during the meditation (“How demanding was the exercise for you?”) and how much they liked it (“How enjoyable was the exercise for you?”) on a 10-point Likert scale (0 = ‘not at all’ to 10 = ‘very much’).

2.3.2. Physiological measures

Cardiac variables including HR and HF-HRV were assessed with electrocardiogram recordings (ECG) that were measured with the Zephyr Bioharness 3 while participants meditated during the weekly meditation sessions (Zephyr, 2014). The Zephyr Bioharness 3 is an ambulatory, multivariable measurement device that was previously validated with standard physiology monitoring systems used in the laboratory (Johnstone et al., 2012). The Zephyr Bioharness 3 device can be attached to a belt that participants can comfortably wear around their chest. The ECG included in the Zephyr Bioharness 3 has a sampling frequency of 250 Hz.

2.4. Data pre-processing of physiological measures

For ECG analysis, 10-minute epochs from the middle of each meditation exercise were extracted using Matlab (Matlab, 2013). The raw ECG data of the 10-minute extracts were then checked for artifacts using a custom-made in-house software. The software automatically detected the QRS complexes of the raw ECG recordings. After the automatic processing step, data were visually inspected by an assistant in order to check whether the QRS complexes were correctly detected. The assistant who checked the data quality was blind to the meditation types. If the software misclassified a QRS complex, or a QRS complex was missing, labels were manually set to the closest QRS complex or the halfway point between two QRS complexes. Data-sets were only fully excluded from further analyses if the data were so noisy that no QRS complexes could be detected. On average 5 ECG files were excluded per measurement time point due to noise. In total 95.30% of the ECG files were included for the statistical analyses. Average HR and HF-HRV (frequency power range: 0.15–0.4 Hz) of the mid 10 minutes of the meditation session were extracted with the software Artiifact (Kaufmann et al., 2011).[1]

2.5. Statistical analysis

Linear Mixed Models (LMM) are often used in studies with repeated measures designs, because observations with missing data from one measurement time point are preserved from a listwise deletion (Kristjansson et al., 2007). Thus we applied LMMs with the within-subject factor time (week 3, week 13) and the within-subject factor type of exercise (breathing meditation, loving-kindness meditation, observing-thoughts meditation) to test 1) whether HR, HF-HRV, effort and likeability differ when comparing loving-kindness meditation and observing-thoughts meditation to breathing meditation, 2) whether HR, HF-HRV, effort and likeability changed from week 3 to week 13 and 3) whether the changes over time are different when comparing loving-kindness meditation and observing-thoughts meditation to breathing meditation. The LMM was run separately for all four dependent variables. It is known that age, body mass index (BMI) and time of the day can influence the cardiovascular system. Thus we controlled for age, BMI, time of the session and also the location of the session in the model.[2] HF-HRV was positively skewed and thus transformed using a natural log transformation. All other dependent variables were normally distributed. Effect sizes of the main effects and interaction effect were calculated with Omega-squared (w^2) by taking the difference from 1 and the variance of the residuals of the full model divided by the variance of the residuals of the model without the respective fixed factor of interest (Xu, 2003). A value of $w^2 = .010$ indicates a small effect size, a value of $w^2 = .059$ represents a medium effect size and a value of $w^2 = .138$ represents a large effect size (Kirk, 1996).

3. Results

3.1. Descriptive statistics

Table 1 provides an overview of the raw descriptive statistics for each type of meditation exercise in week 3 and week 13.

3.2. Difference across types of exercises

In accordance with hypothesis 1, results of the LMM analysis revealed significant differences between types of exercises for HR, effort and likeability (Fig. 1 and Table 2). No significant difference between types of exercises was found for HF-HRV (Table 2). Bonferroni-corrected pairwise comparisons confirm our hypothesis that HR during breathing meditation is lower compared to loving-kindness meditation ($t(590) = -2.230$, $p < .001$, 95% CI [−3.487, −.973]) and observing-thoughts meditation ($t(590) = -1.308$, $p = .039$, 95% CI [−2.567, −.049]). Also in line with hypothesis 1, experienced effort is lower during breathing meditation compared to loving-kindness meditation ($t(637) = -.858$, $p < .001$, 95% CI [−1.269, −.447]) and observing-thoughts meditation ($t(639) = -.522$, $p = .008$, 95% CI [−.939, −.105]). Experienced likeability was significantly higher for breathing meditation compared to loving-kindness meditation ($t(630) = .846$, $p < .001$, 95% CI [.490, 1.201]), but not compared to observing-thoughts meditation ($t(632) = .246$, $p = .309$, 95% CI [−.115, .607]). Effect sizes for HR and likeability are medium and effect sizes for HF-HRV and effort are small (Table 2).

3.3. Change with training over time

The LMM analysis showed that, as hypothesized, the subjective experience of effort decreased ($t(632) = -.697$, $p < .001$, 95% CI [−.973, −.422]) while the subjective experience of likeability increased after 10 weeks of training ($t(624) = .837$, $p < .001$, 95% CI [.598, 1.075]) (see Fig. 2 and Table 2). These findings point to training progress when regarding participants' subjective point of view. Contrary to our prediction HR increased from week 3 to week 13 ($t(587) = 2.628$, $p < .001$, 95% CI [1.798, 3.459]) and HF-HRV decreased over time ($t(594) = -.214$, $p < .001$, 95% CI [−.321, −.107]) (Table 2 and Fig. 2). HR and likeability have medium effect sizes and HF-HRV and effort have small effect sizes (Table 2). An additional analysis to test how HR and HF-HRV are related to effort and likeability showed that, for HR only, week 13 HR was positively correlated with week 13 effort. All other correlations between self-report and physiological data were non-significant (see Supplementary material for further details).

3.4. Difference in training over time across exercises

We expected that changes over time vary across types of exercises and more specifically that a decrease in HR and effort and an increase in HF-HRV and likeability would be smaller during loving-kindness meditation and observing-thoughts meditation compared to breathing meditation (hypothesis 3). The LMM analysis revealed a significant interaction between the main effect of time and main effect of the type of exercise for the physiological, but not for the subjective measures (Table 2). Bonferroni-corrected contrasts revealed a significant increase in HR during loving-kindness meditation ($t(586) = 4.926$, $p < .001$, 95% CI [3.493, 6.359]) and observing-thoughts meditation ($t(585) = 2.523$, $p = .001$, 95% CI [1.095, 3.952]) from week 3 to week 13, but no significant changes in HR during breathing meditation ($t(591) = .435$, $p = .557$, 95% CI [−1.021, 1.892]) (Fig. 3). In addition HF-HRV significantly decreased during loving-kindness meditation ($t(593) = -.339$, $p < .001$, 95% CI [−.524, −.154]) and observing-thoughts meditation ($t(591) = -.309$, $p = .001$, 95% CI [−.493, −.125]) but not during breathing meditation ($t(599) = .006$, $p = .952$, 95% CI [−.182, .193]) from week 3 to week 13 (Fig. 3). Both HR and HF-HRV have small effect sizes (Table 2). To statistically test whether the changes over time differ across types of exercises we ran a LMM analysis using difference scores of subtracting week 3 from week 13. The type of exercise (breathing meditation, loving-kindness meditation and observing-thoughts meditation) was used as a within-subject factor. Results showed a significant effect of the type of exercise for HR ($F(2, 196) = 13.28$, $p < .001$) with a large effect size ($w^2 = 0.18$) and a significant effect of the type of exercise for HF-HRV ($F(2, 230) = 5.09$, $p = .007$) with a medium effect size ($w^2 = 0.07$). Contrary to our prediction, Bonferroni-corrected contrasts revealed that the changes in HR over time were significantly larger for loving-kindness meditation ($t(203) = 5.237$, $p < .001$, 95% CI [2.784, 7.690]) and observing-thoughts meditation ($t(195) = 2.803$, $p = .018$, 95% CI [.369, 5.238]) compared to breathing meditation. Also in contrast to our hypothesis, changes in HF-HRV over time were greater for loving-kindness meditation ($t(237) = -.397$, $p = .015$, 95% CI [−.736, −.059]) and observing-thoughts meditation ($t(229) = -.383$, $p = .020$, 95% CI [−.721, −.045]) compared to breathing meditation.

[1] Because of data loss from the weekly recordings during the second measurement of cohort 1 in the Leipzig morning group we performed the same statistical analyses by excluding the data from the morning group in Leipzig of training cohort 1, which included 17 participants. The pattern of the results stayed consistent with the results as presented in the Results section. The data loss was due to changes in the structure of the weekly session during the second measurement of the first training module from the morning group in Leipzig of training cohort 1. Due to the changes of the session the duration of the meditation was shortened from 20 minutes to 3.5 minutes.

[2] All analyses were rerun without the control variables (age, BMI, time of session, location of session) to test whether the patterns of results stayed statistically significant. Results without the control variables revealed the same statistical pattern of results as compared to the results from the analyses that included the control variables.

Table 1
Raw means and standard deviations for each meditation exercise in week 3 and week 13.

	Breathing meditation				Loving-kindness meditation				Observing-thoughts meditation			
	Week 3		Week 13		Week 3		Week 13		Week 3		Week 13	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
HR	70.62	9.55	71.39	11.12	71.24	10.26	75.96	10.50	71.38	9.34	74.19	11.67
HF-HRV	5.68	1.11	5.67	1.04	5.75	1.15	5.37	1.21	5.74	1.15	5.41	1.14
Effort	3.84	2.53	2.69	2.23	4.33	2.52	3.77	2.48	4.03	2.44	3.43	2.41
Likeability	6.67	2.06	7.68	1.90	5.84	2.23	6.88	2.06	6.66	1.83	7.73	1.98

Note: HR = heart rate, HF-HRV = high-frequency heart rate variability.

4. Discussion

The goal of the current study was to investigate how three types of meditation, which differ with respect to cognitive demands, influence cardiac activity and experienced effort and enjoyment with training over time. In line with hypothesis 1, HR and effort were lowest for breathing meditation compared to loving-kindness meditation and observing-thoughts meditation. These findings support our assumption that loving-kindness meditation and observing-thoughts meditation are more demanding than breathing meditation, because they require a greater amount of cognitive effort. Participants enjoyed loving-kindness meditation less than the breathing meditation, whereas they experienced the breathing meditation and observing-thoughts meditation as equally pleasant. Overall these findings support our expectations that both loving-kindness meditation and observing-thoughts meditation are subjectively more challenging and physiologically more arousing for the participants when compared to breathing meditation. This suggests that not all types of meditation elicit similar responses and further support the need to study the effects of different types of meditation.

Regarding the effect of training over time, independent of the type of exercise, our results showed that participants subjectively perceive the meditation exercises as less effortful over training and that, overall, they enjoy meditation more after training than before. These findings confirm our hypothesis that the training induces changes in the participants' subjective experience with increased familiarity with the exercises and supports previous research on meditation-induced changes in cognitive effort (Tang et al., 2012; Zanesco et al., 2013). We further hypothesized that as participants get more accustomed with the training the activation of the PNS would increase over time. Contrary to our prediction, however, it was SNS activity that increased after the training and not PNS activity as reflected in an increase in HR and decrease in HF-HRV. These findings suggest that gaining expertise in these types of demanding mental exercises induced an increase in sympathetic arousal over training, while at the same time, participants experienced the exercises as more enjoyable and less effortful over training. The increased physiological arousal over training could indicate that with increased expertise participants may make usage of more attentional and cognitive resources required for a better mastery of the task. Thus, for example, they may make more usage of visual

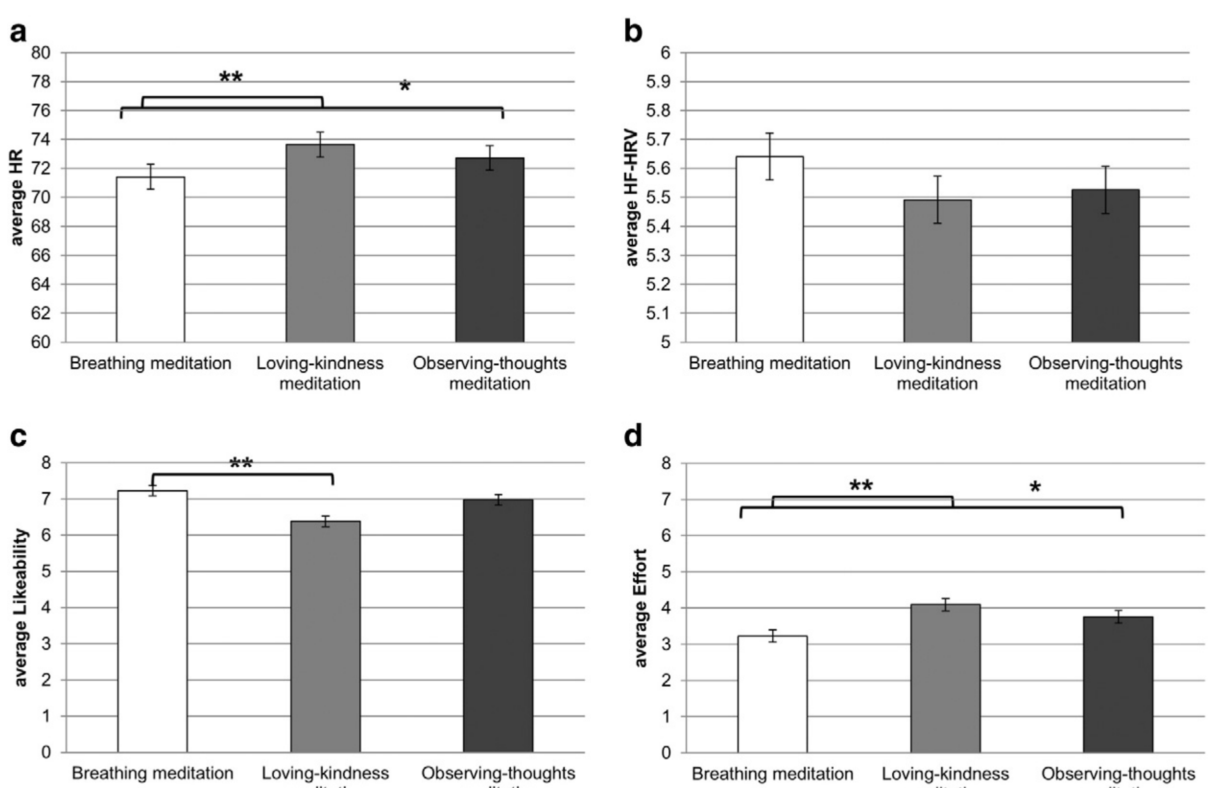

Fig. 1. Estimated marginal means from breathing meditation, loving-kindness meditation and observing-thoughts meditation for a) HR, b) HF-HRV, c) likeability ratings and d) effort ratings (P* < .05; P** < .01).

Table 2
Results of Linear Mixed Model analyses: main effects of time and exercise and the interaction effect of time and exercise.

Source	Numerator df/denominator df	F	w^2
HR			
Exercise	2/589.33	9.134***	0.061
Time	1/587.46	38.65***	0.092
Time × exercise	2/587.63	9.35***	0.030
HF-HRV			
Exercise	2/597.93	2.65	0.026
Time	1/594.45	15.41***	0.039
Time × exercise	2/594.86	4.04*	0.015
Effort			
Exercise	2/636.77	12.69***	0.052
Time	1/632.21	24.68***	0.046
Time × exercise	2/630.89	2.57	0.009
Likeability			
Exercise	2/629.28	17.30***	0.060
Time	1/624.34	47.50***	0.072
Time × exercise	2/622.96	.63	0.002

Note: *P < .05; **P < .01; ***P < .001. Age, gender, BMI, time and location of session were included as covariates. $w^2 = 0.010$ corresponds to a small effect size, $w^2 = 0.059$ represents a medium effect size and $w^2 = 0.135$ represents a large effect size.

imagery or processes which facilitate attention and meta-cognitive awareness on the objects of introspection in their minds. The results show that, despite an increase in physiological effort, subjects have learned to subjectively enjoy this state of high concentration and mastery and thus perceive it subjectively as less effortful; similarly to earlier research about states of flow while someone is engaged during a challenging task (Csikszentmihalyi, 2014). This finding is also in line with the assumption that with greater training experience meditation can lead to an increase in wakefulness and alertness (Britton et al., 2014). On the other hand this finding could also indicate that participants' subjective experiences do not fully capture their autonomic states during meditation. A significant correlation between the physiological and subjective measures was found only for week 13 HR and week 13 effort (see Supplementary material for further details). This suggests that with greater expertise the physiological measures and subjective measures become more coherent (Sze et al., 2010). These findings relate to a general theoretical discussion about the reliability of self-reports, motivating the need to conduct further research that allows for the development and identification of more subtle subjective measures that can accurately capture physiological processes (Nisbett and Wilson, 1977; Petitmengin and Lachaux, 2013).

In addition the interaction effect of difference across exercises in change with training over time showed an increase in HR and decrease in HF-HRV for both loving-kindness meditation and observing-thoughts meditation, but not for breathing meditation with training over 10 weeks. More specifically changes in HR and HF-HRV over time were both greater for loving-kindness meditation and observing-thoughts meditation when compared to breathing meditation. This suggests that getting better in both loving-kindness meditation and observing-thoughts meditation over training leads to an increase in activation of the sympathetic system, whereas practicing breathing meditation does not lead to any changes in cardiac responses. These findings could indicate that the increased physiological arousal allows the participants to better master the loving-kindness meditation and observing-thoughts meditation, which are cognitively more demanding than the breathing meditation. In addition to sustaining and redirecting attention to the object of focus, loving-kindness meditation and observing-thoughts meditation involve more complex cognitive processes such as the generation of mental imagery and positive affect, focusing on complex objects of attention including emotions and thoughts, categorization and detachment from thoughts, as well as maintaining meta-awareness. In A study by Amihai & Kozhevnikov,

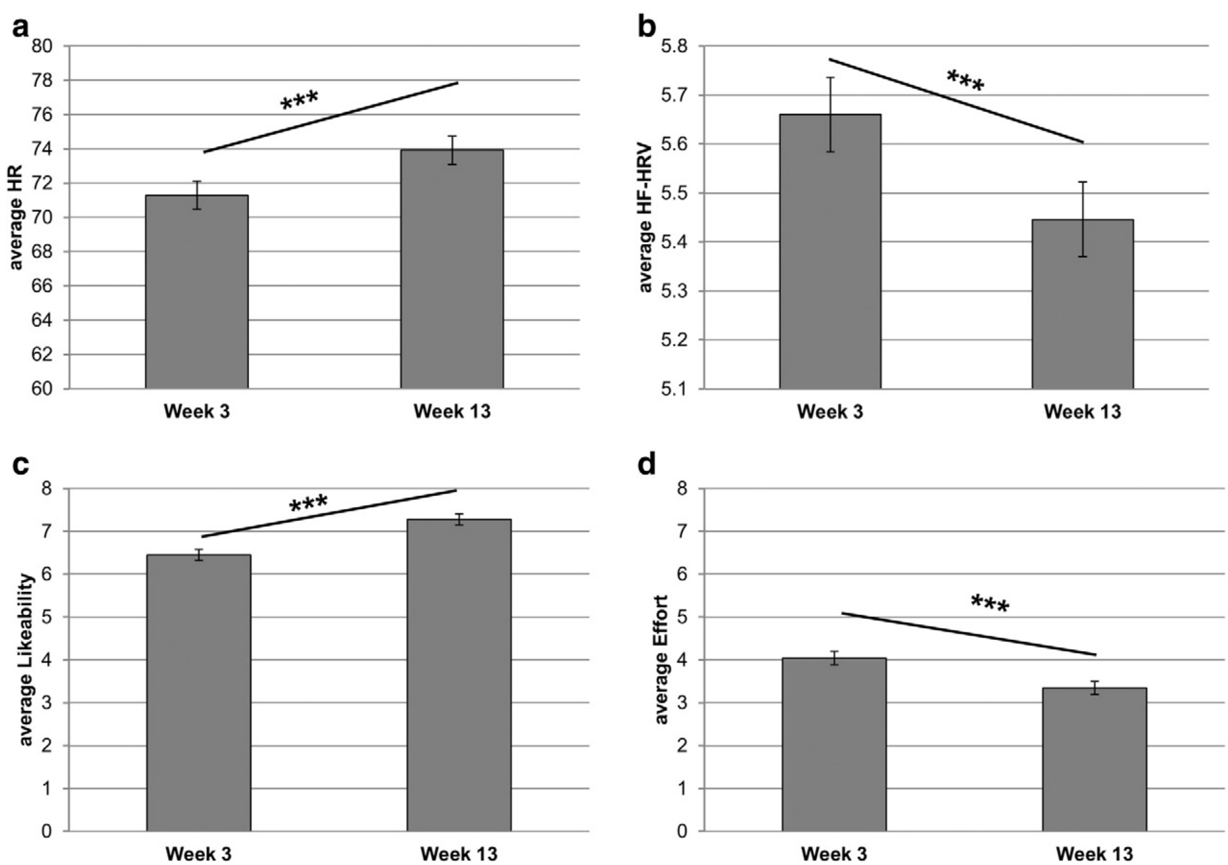

Fig. 2. Estimated marginal means from week 3 and week 13 for a) HR, b) HF-HRV, c) likeability ratings and d) effort ratings (P*** < .001).

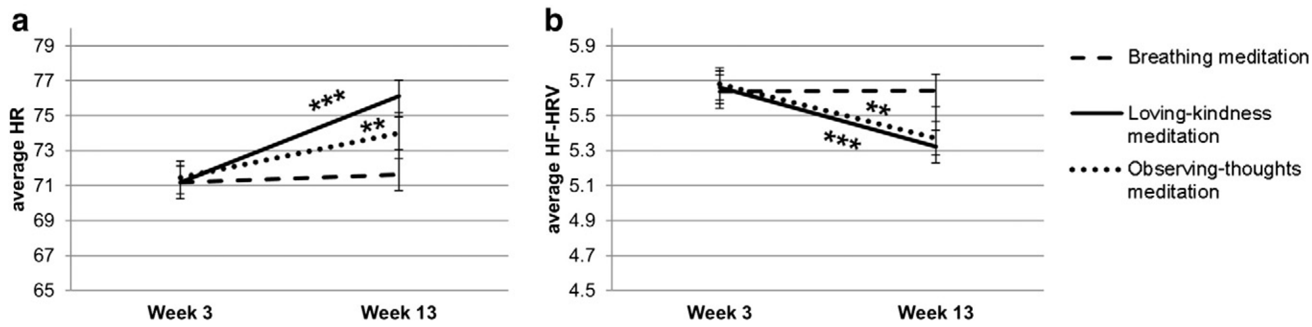

Fig. 3. Estimated marginal means for a) HR and b) HF-HRV comparing week 3 and week 13 for breathing meditation, loving-kindness meditation and observing-thoughts meditation ($P^{**} < .01$; $P^{***} < .001$).

types of meditation that involve active processes such as the generation of imagery induced SNS activity when compared to types of meditation that just involve sustained attention such as in breathing meditation (Amihai and Kozhevnikov, 2014). Accordingly, the increase in activation of the SNS during loving-kindness meditation and observing-thoughts meditation with training over time could imply an increase in overall phasic alertness based on physiological arousal, which serves as a physiological resource for the increased cognitive demands during these types of meditation. Finally the lack of correlation between changes in HR and changes in effort during loving-kindness meditation and observing-thoughts meditation shows that the increase in physiological arousal is subjectively not experienced as effortful (see Supplementary material for further details). This could suggest that the increase in physiological arousal is not a marker of effort, but rather a marker of increased cognitive resources.

Findings from the current study are limited in some ways. First the current study did not include a baseline measurement of HR and HF-HRV right before the meditation session. Including a baseline measurement could reveal helpful information about whether the three types of meditation studies influence cardiac activity differently when comparing meditation to the baseline condition. Additionally the current study looked at the average score of HR and HF-HRV from a 10-minute sample of the meditation session. More fine-grained information could be revealed with analyzing the ECG data continuously. Finally including a control group was not feasible in the current study, however future studies could compare the effects of different types of meditation over a short-term training on cardiac variables by including an active-control group such as a reading control group that involves attentional, affective and cognitive resources as required in the investigated meditation exercises (Allen et al., 2012).

Overall the current study showed that not all types of meditation are equally relaxing when comparing three different types of meditation. Furthermore the study showed that with training participants enjoy the mental exercises more and experience it as less effortful on a subjective level, while at the same time training the two types of more complex meditations comes with an increase in sympathetic activation, suggesting heightened mastery and concentration needed with increasing expertise. Such findings are important, because they show that different types of meditation should be recommended for different purposes. Breathing meditation was perceived as the least effortful exercise and also had the lowest HR, which makes it suitable for an easy to learn exercise for meditation novices. This is in line with descriptions from Buddhist traditions, in which breathing meditation is used as a foundational exercise in Shamatha meditation (Wallace, 2006). Loving-kindness meditation and observing-thoughts meditation were both perceived as more effortful than breathing meditation which was also reflected in a higher HR which increased with training experience. Therefore individuals with related health problems, or anxiety disorders which are known to be related to increased cardiac arousal, might not benefit from loving-kindness meditation and observing-thoughts meditation (Gorman and Sloan, 2000). Future studies should investigate whether loving-kindness meditation and observing-thoughts meditation induced increases in HR are related to improvements in cognitive performance as suggested by Amihai & Kozhevnikov (Amihai and Kozhevnikov, 2014). If this is the case exercises such as loving-kindness meditation and observing-thoughts meditation could be recommended for increasing phasic alertness for improved cognitive task performance. To make more fine-grained suggestions about the applicability of meditation exercises in different domains, future studies should investigate changes of physiological, cognitive and affective signatures of meditation state in both healthy and clinical populations.

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Conflict of interest statement

The authors declare that there are no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ijpsycho.2015.04.017.

References

Allen, M., Dietz, M., Blair, K.S., van Beek, M., Rees, G., Vestergaard-Poulsen, P., Lutz, A., Roepstorff, A., 2012. Cognitive-affective neural plasticity following active-controlled mindfulness intervention. J. Neurosci. 32 (44), 15601–15610. http://dx.doi.org/10.1523/JNEUROSCI.2957-12.2012.

Amihai, I., Kozhevnikov, M., 2014. Arousal vs. relaxation: a comparison of the neurophysiological and cognitive correlates of Vajrayana and Theravada meditative practices. PLoS One 9 (7), e102990. http://dx.doi.org/10.1371/journal.pone.0102990.

Benson, H., Beary, J.F., Carol, M.P., 1974. The relaxation response. Psychiatry J. Study Interpers. Process. 37 (1). http://dx.doi.org/10.1521/00332747.1974.11023785.

Billman, G.E., 2011. Heart rate variability–a historical perspective. Front. Physiol. 2 (86), 1–13. http://dx.doi.org/10.3389/fphys.2011.00086.

Britton, W.B., Lindahl, J.R., Cahn, B.R., Davis, J.H., Goldman, R.E., 2014. Awakening is not a metaphor: the effects of Buddhist meditation practices on basic wakefulness. Ann. N. Y. Acad. Sci. 1307, 64–81. http://dx.doi.org/10.1111/nyas.12279.

Camm, A., Malik, M., Bigger, J., Breithardt, G., Cerutti, S., Cohen, R., Coumel, P., Fallen, E., Kleiger, R., Lombardi, F., 1996. Heart rate variability: standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of

Cardiology and the North American Society of Pacing and Electrophysiology. Circulation 93 (1), 1043–1065. http://dx.doi.org/10.1161/01.CIR.93.5.1043.

Critchley, H.D., Eccles, J., Garfinkel, S.N., 2013. Interaction between cognition, emotion, and the autonomic nervous system. Handb. Clin. Neurol. 117, 59–77. http://dx.doi.org/10.1016/B978-0-444-53491-0.00006-7.

Csikszentmihalyi, M., 2014. Flow and the Foundations of Positive Psychology. Springer, London.

Csikszentmihalyi, M., LeFevre, J., 1989. Optimal experience in work and leisure. J. Pers. Soc. Psychol. 56 (5), 815–822. http://dx.doi.org/10.1037/0022-3514.56.5.815.

Gorman, J.M., Sloan, R.P., 2000. Heart rate variability in depressive and anxiety disorders. Am. Heart J. 140 (4), S77–S83. http://dx.doi.org/10.1067/mhj.2000.109981.

Hansen, A.L., Johnsen, B.H., Thayer, J.F., 2003. Vagal influence on working memory and attention. Int. J. Psychophysiol. 48 (3), 263–274. http://dx.doi.org/10.1016/S0167-8760(03)00073-4.

Hofmann, S.G., Grossman, P., Hinton, D.E., 2011. Loving-kindness and compassion meditation: Potential for psychological interventions. Clin. Psychol. Rev. 31 (7), 1126–1132. http://dx.doi.org/10.1016/j.cpr.2011.07.003.

Hölzel, B.K., Lazar, S.W., Gard, T., Schuman-Olivier, Z., Vago, D.R., Ott, U., 2011. How does mindfulness meditation work? Proposing mechanisms of action from a conceptual and neural perspective. Perspect. Psychol. Sci. 6 (6), 537–559. http://dx.doi.org/10.1177/1745691611419671.

Jevning, R., Wallace, R., Beidebach, M., 1992. The physiology of meditation: A review. A wakeful hypometabolic integrated response. Neurosci. Biobehav. Rev. 16 (3), 415–424. http://dx.doi.org/10.1016/S0149-7634(05)80210-6.

Johnstone, J.A., Ford, P.A., Hughes, G., Watson, T., Garrett, A.T., 2012. Bioharness™ multivariable monitoring device: part. I: Validity. J. Sports Sci. Med. 11 (3), 400–408.

Kaufmann, T., Sutterlin, S., Schulz, S.M., Vogele, C., 2011. ARTiiFACT: a tool for heart rate artifact processing and heart rate variability analysis. Behav. Res. Methods 43 (4), 1161–1170. http://dx.doi.org/10.3758/s13428-011-0107-7.

Kirk, R.E., 1996. Practical significance: a concept whose time has come. Educ. Psychol. Meas. 56 (5), 746–759. http://dx.doi.org/10.1177/0013164496056005002.

Kok, B.E., Waugh, C.E., Fredrickson, B.L., 2013. Meditation and health: The search for mechanisms of action. Soc. Personal. Psychol. Compass 7, 27–39. http://dx.doi.org/10.1111/spc3.12006.

Kristjansson, S.D., Kircher, J.C., Webb, A.K., 2007. Multilevel models for repeated measures research designs in psychophysiology: An introduction to growth curve modeling. Psychophysiology 44 (5), 728–736. http://dx.doi.org/10.1111/j.1469-8986.2007.00544.x.

Krygier, J.R., Heathers, J.A., Shahrestani, S., Abbott, M., Gross, J.J., Kemp, A.H., 2013. Mindfulness meditation, well-being, and heart rate variability: A preliminary investigation into the impact of intensive Vipassana meditation. Int. J. Psychophysiol. 89 (5), 305–313. http://dx.doi.org/10.1016/j.ijpsycho.2013.06.017.

Lazar, S.W., Bush, G., Gollub, R.L., Fricchione, G.L., Khalsa, G., Benson, H., 2000. Functional brain mapping of the relaxation response and meditation. Neuroreport 11 (7), 1581–1585. http://dx.doi.org/10.1097/00001756-200005150-00041.

Libby, D.J., Worhunsky, P.D., Pilver, C.E., Brewer, J.A., 2012. Meditation-induced changes in high-frequency heart rate variability predict smoking outcomes. Front. Hum. Neurosci. 6. http://dx.doi.org/10.3389/fnhum.2012.00054.

Luft, C.D.B., Takase, E., Darby, D., 2009. Heart rate variability and cognitive function: Effects of physical effort. Biol. Psychol. 82 (2), 186–191. http://dx.doi.org/10.1016/j.biopsycho.2009.07.007.

Lutz, A., Greischar, L.L., Perlman, D.M., Davidson, R.J., 2009. BOLD signal in insula is differentially related to cardiac function during compassion meditation in experts vs. novices. Neuroimage 47 (3), 1038–1046. http://dx.doi.org/10.1016/j.neuroimage.2009.04.081.

Malinowski, P., 2013. Neural mechanisms of attentional control in mindfulness meditation. Front. Neurosci. 7. http://dx.doi.org/10.3389/fnins.2013.00008.

Matlab, 2013. 8.2, MathWorks Inc, Natick, MA.

Mrazek, M.D., Franklin, M.S., Phillips, D.T., Baird, B., Schooler, J.W., 2013. Mindfulness training improves working memory capacity and GRE performance while reducing mind wandering. Psychol. Sci. 24, 776–781. http://dx.doi.org/10.1177/0956797612459659.

Nisbett, R.E., Wilson, T.D., 1977. Telling more than we can know: Verbal reports on mental processes. Psychol. Rev. 84 (3), 231–259. http://dx.doi.org/10.1037/0033-295X.84.3.231.

Olex, S., Newberg, A., Figueredo, V.M., 2013. Meditation: should a cardiologist care? Int. J. Cardiol. 168 (3), 1805–1810. http://dx.doi.org/10.1016/j.ijcard.2013.06.086.

Overbeek, T.J., van Boxtel, A., Westerink, J.H., 2014. Respiratory sinus arrhythmia responses to cognitive tasks: Effects of task factors and RSA indices. Biol. Psychol. 99, 1–14. http://dx.doi.org/10.1016/j.biopsycho.2012.02.006.

Peng, C.-K., Henry, I.C., Mietus, J.E., Hausdorff, J.M., Khalsa, G., Benson, H., Goldberger, A.L., 2004. Heart rate dynamics during three forms of meditation. Int. J. Cardiol. 95 (1), 19–27. http://dx.doi.org/10.1016/j.ijcard.2003.02.006.

Petitmengin, C., Lachaux, J.-P., 2013. Microcognitive science: bridging experiential and neuronal microdynamics. Front. Hum. Neurosci. 7. http://dx.doi.org/10.3389/fnhum.2013.00617.

Reyes del Paso, G.A., Langewitz, W., Mulder, L.J., Roon, A., Duschek, S., 2013. The utility of low frequency heart rate variability as an index of sympathetic cardiac tone: A review with emphasis on a reanalysis of previous studies. Psychophysiology 50 (5), 477–487. http://dx.doi.org/10.1111/psyp.12027.

Singer, T., Kok, B.E., Bolz, M., Bornemann, B., Bochow, C.A., 2015n. The Resource Project: Background, Design, Samples, and Measurements (in preparation), Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig.

Slagter, H.A., Davidson, R.J., Lutz, A., 2011. Mental training as a tool in the neuroscientific study of brain and cognitive plasticity frontiers in human. Neuroscience 5, 1–12. http://dx.doi.org/10.3389/fnhum.2011.00017.

Sze, J.A., Gyurak, A., Yuan, J.W., Levenson, R.W., 2010. Coherence between emotional experience and physiology: Does body awareness training have an impact? Emotion 10 (6), 803. http://dx.doi.org/10.1037/a0020146.

Takahashi, T., Murata, T., Hamada, T., Omori, M., Kosaka, H., Kikuchi, M., Yoshida, H., Wada, Y., 2005. Changes in EEG and autonomic nervous activity during meditation and their association with personality traits. Int. J. Psychophysiol. 55 (2), 199–207. http://dx.doi.org/10.1016/j.ijpsycho.2004.07.004.

Tang, Y.-Y., Rothbart, M.K., Posner, M.I., 2012. Neural correlates of establishing, maintaining, and switching brain states. Trends Cogn. Sci. 16 (6), 330–337. http://dx.doi.org/10.1016/j.tics.2012.05.001.

Thayer, J.F., Lane, R.D., 2009. Claude Bernard and the heart–brain connection: Further elaboration of a model of neurovisceral integration. Neurosci. Biobehav. Rev. 33 (2), 81–88. http://dx.doi.org/10.1016/j.neubiorev.2008.08.004.

Wallace, B.A., 1999. The Buddhist tradition of Samatha: Methods for refining and examining consciousness. J. Conscious. Stud. 6, 175–187.

Wallace, B.A., 2006. The attention revolution: unlocking the power of the focused mind. Wisdom Publications, Boston, MA.

Wu, S.-D., Lo, P.-C., 2008. Inward-attention meditation increases parasympathetic activity: a study based on heart rate variability. Biomed. Res. 29 (5), 245–250. http://dx.doi.org/10.2220/biomedres.29.245.

Xu, R., 2003. Measuring explained variation in linear mixed effects models. Stat. Med. 22 (22), 3527–3541. http://dx.doi.org/10.1002/sim.1572.

Zanesco, A.P., King, B.G., MacLean, K.A., Saron, C.D., 2013. Executive control and felt concentrative engagement following intensive meditation training. Front. Hum. Neurosci. 7. http://dx.doi.org/10.3389/fnhum.2013.00566.

Zeidan, F., Johnson, S.K., Diamond, B.J., David, Z., Goolkasian, P., 2010a. Mindfulness meditation improves cognition: Evidence of brief mental training. Conscious. Cogn. 19 (2), 597–605. http://dx.doi.org/10.1016/j.concog.2010.03.014.

Zeidan, F., Johnson, S.K., Gordon, N.S., Goolkasian, P., 2010b. Effects of brief and sham mindfulness meditation on mood and cardiovascular variables. J. Altern. Complement. Med. 16 (8), 867–873. http://dx.doi.org/10.1089/acm.2009.0321.

Zephyr, 2014. Zeyphr. http://www.zephyr-technology.com/.