Appl Psychophysiol Biofeedback (2016) 41:315–329
DOI 10.1007/s10484-016-9332-2

The Sensorium: Psychophysiological Evaluation of Responses to a Multimodal Neurofeedback Environment

Thilo Hinterberger[1] · Elena Fürnrohr[1]

Published online: 29 March 2016

Abstract The Sensorium is a multimodal neurofeedback environment that reflects a person's physiological state by presenting physiological signals via orchestral sounds from a speaker and multi-coloured lights projected onto a white surface. The software manages acquisition, real-time processing, storage, and sonification of various physiological signals such as the electroencephalogram (EEG) or electrocardiogram (ECG). Each of the 36 participants completed 6 interventional conditions consisting of three different Sensorium-phases with EEG and ECG feedback, a mindfulness meditation, a guided body scan exercise, and a Pseudo-Sensorium using pre-recorded data that did not reflect the subject's own physiology. During all phases EEG, ECG, skin conductance, and respiration were recorded. A feedback questionnaire assessed the participants' subjective reports of changes in well-being, perception, and life-spirit. The results indicate that the Sensorium sessions were not statistically inferior compared to their corresponding active control conditions with respect to improvements in subjective reports concerning well-being and perception. Additionally, the Sensorium was rated as being a more extraordinary experience, as compared to meditation. During the Sensorium conditions the EEG showed lower levels of theta2 (7–8.5 Hz), alpha (9–12 Hz) and beta (12.5–25 Hz) activity. Since participants reported benefit from the Sensorium experience regardless of any prior experience with meditation, we propose this novel method of meditative and extraordinary self-experience to be utilized as a modern alternative to more traditional forms of meditation.

Keywords Sensorium · EEG · Neurofeedback · Mindfulness · Meditation

✉ Thilo Hinterberger
Thilo.Hinterberger@ukr.de

[1] Research Section of Applied Consciousness Sciences, Department of Psychosomatic Medicine, University Hospital Regensburg, Franz-Joseph-Strauß-Allee 11, 93053 Regensburg, Germany

Introduction

The broad spectrum of methods to reduce stress and support relaxation comprises general relaxation, including muscle relaxation such as the Jacobson method (Jacobson 1938), mental relaxation such as autogenic training (Stetter and Kupper 2002) as well as biofeedback and neurofeedback methods (Thompson and Thompson 2007) among others. Feedback technologies mostly use specific body signals, such as electrical signals from muscles, heart, or brain, (electroencephalogram, EEG) that are usually filtered and fed back on a computer screen. The user has to manipulate the feedback graph or image, thereby learning to self-regulate his or her own physiology that relates to the symptoms of stress or other disorders. As a non-technological method Mindfulness-Based Stress Reduction (MBSR) is increasingly popular and is "recommended as a useful method for improving mental health and reducing symptoms of stress, anxiety and depression" (Fjorback et al. 2011). Mindfulness, which is defined as being aware of the current moment by non-judgmental perception, can be practiced in an 8-week MBSR course that requires the practice of two different mindfulness exercises; namely, mindfulness meditation and body scan meditation (Ludwig and Kabat-Zinn 2008). Time spent practicing these meditation exercises is significantly related to the extent of improvement in most facets of mindfulness and several measures of symptoms and well-being, including perceived stress, somatization, depression, anxiety, interpersonal sensitivity, psychoticism, and paranoia (Carmody and Baer 2008; Malinowski 2008, 2013). According to the Liverpool Mindfulness Model (Malinowski 2013) mindfulness practice is modulated through motivation, intention, expectations, and attitudes. While each of the above mentioned methods contributes to the enhancement of well-being, we present a novel technology of neurofeedback—the Sensorium—that combines essential principles of mindfulness practices (Hinterberger 2011) as follows:

(1) The Sensorium provides feedback of (neuro-) physiological body signals such as the EEG and ECG (electrocardiogram) in an aesthetic fashion through sounds and lights. Thereby, it offers an *enhanced self-perception* of inner body signals displayed in the outer environment. This allows the participants to be aware of their own body processes in the *present moment*.
(2) The participants were instructed *not* to alter the signals intentionally but just perceive them in a *non-judgmental attitude*. They were not given any specific information about the meaning of the sounds and the lights in advance in order to avoid cognitive involvement and judgments during the feedback experience.
(3) The whole setting, the guidance, and the environment supported a *positive attitude* and the *expectation* of an extraordinary experience.

Thus, the Sensorium employs an extraordinary audiovisual presentation of a person's psychophysiology with respect to brain waves and heart rate in the present moment in order to facilitate non-judgmental awareness in the present moment. In Sensorium sessions we carefully implemented these principles of mindfulness in order to successfully modulate physical and mental well-being. This report presents subjective ratings and physiological data from such multimodal feedback sessions and compares those results to mindfulness exercises and a pseudo-feedback session as active control conditions.

Methods

Technology

The Sensorium technology can be separated into three different functional elements: (1) software, (2) hardware, and (3) environment.

Software

The Sensorium software uses functional components of the brain-computer interface Thought-Translation-Device (Birbaumer et al. 1999; Hinterberger et al. 2004, 2003). A component for orchestral sonification of EEG in real-time (POSER) was developed to provide feedback of the ongoing EEG with a number of different musical instruments (Hinterberger 2007, 2011; Hinterberger and Baier 2005). The Sensorium software can be interfaced to several commercial neurosignal amplifier systems. It allows for data storage for offline analysis, display of physiological data, real-time signal processing and sonification. In a first signal processing step EEG data are filtered into specific frequency bands that were used as feedback signals. We chose the bands: USP (0.01–0.2 Hz, ultra-slow potentials), SCP (0.1–1 Hz, slow cortical potentials), delta1 (0.5–2 Hz), delta2 (2–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–25 Hz), gamma (25–40 Hz), wide (1–40 Hz). For sonification each maximum of a band-filtered signal touches a key of a musical instrument provided by a software sampler. The amplitude of the wave determines the velocity of a key stroke (which determines its loudness) while the pitch is determined by the time from peak-to-peak of a wave cycle. This is the most common sonification method used in the present study (for a more detailed description see Hinterberger (2007, 2011) and Hinterberger and Baier (2005). The sonification module sends out MIDI-commands to the VSampler 3.54 (Speedsoft) software sampler with a self-arranged sample bank. For illumination the system converts the filtered signals into DMX codes which thereafter drive a studio-light system. The transformation rules are described in the Experimental conditions.

Hardware

In the present measurement we used a NeXus-10 biosignal amplifier for signal acquisition (Mindmedia B.V., Netherlands). EEG and ECG were recorded with a resolution of 22 bit and a sampling rate of 256 samples/second in a frequency range from DC to 40 Hz. Additionally, skin conductance and respiration were measured. Signals were transmitted via Bluetooth to the PC. For visual feedback we used two three-colored LED flood lights which were interfaced to the computer with a USB-DMX converter. The sounds were presented via two high quality loudspeakers (NuVero4, Nubert, Germany) driven by a high quality stereo amplifier.

The Sensorium Environment

The Sensorium was built up in a room of about 17 m^2 which was divided into two parts, the area of the supervisor and the experience area in which the participant was seated (Fig. 1). During the feedback experience the technology itself should be invisible to the user. The projection area was covered with white cloth to provide a neutral visible field.

Study Design

Three Sensorium settings were tested. The first (Sensorium1) provided feedback of ECG measures while the two others (Sensorium2 and Sensorium3) provided feedback of both, ECG and EEG measures. While Sensorium 1 was compared to a mindfulness meditation session, Sensorium2 was compared to a body scan meditation and a Sensorium3 setting was compared to a so-called Pseudo-Sensorium condition which provided similar light and sound stimuli from pre-recorded data of another person.

Research Questions

With respect to the subjective feedback ratings, two kinds of hypothesis were of interest: (1) We hypothesize that the Sensorium sessions are rated differently from the control conditions, and (2) the Sensorium sessions are rated as being equivalent to (that is not worse than) the corresponding active control conditions. Specifically we tested the following hypotheses H1-H3 and answered the research questions H4 and H5:

(1) **H1**. The ratings of the Sensorium sessions are different compared to the control conditions and the ratings of the Sensorium settings 1–3 are also different from each other.

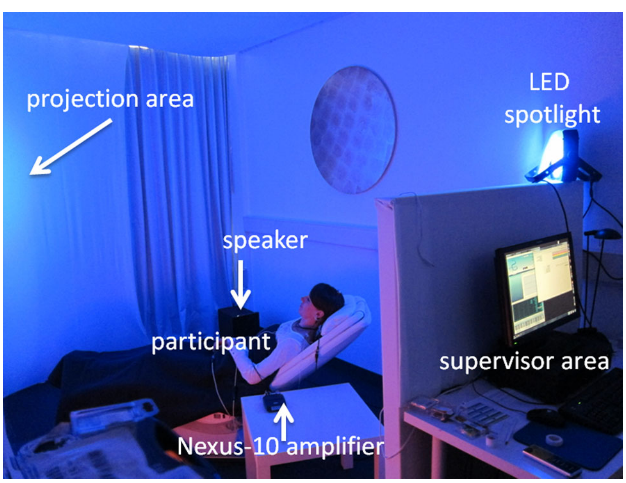

Fig. 1 The experimental room. The feedback environment was separated from the technical equipment

(2) **H2**. The Sensorium is not inferior to the control condition.

   a. The ratings of the Sensorium1 session are not significantly worse than the ratings of the mindfulness meditation.
   b. The ratings of the Sensorium2 session are not significantly worse than the ratings of the body scan exercise.
   c. The Pseudo-Sensorium ratings are significantly worse than the real Sensorium setting 3.
   d. The Sensorium3 ratings are not significantly worse than the Sensorium2 setting.

(3) **H3**. Participants without meditation experience give more positive ratings from the Sensorium conditions compared to participants with meditation experience. Due to the lack of previous data from the Sensorium we did not hypothesize any physiological outcome. Instead, an exploratory approach was chosen to investigate the behavior of the physiological measures. The following research questions were asked here:

(4) **H4**. How did the physiological measures change during each of the six intervention conditions?

(5) **H5**. How do the two conditions of each experimental day compare to each other? We asked how are physiological measures different between

   a. all Sensorium settings and all non-Sensorium settings
   b. Sensorium1 and mindfulness meditation?
   c. Sensorium2 and body scan exercise?
   d. Sensorium3 and Pseudo-Sensorium?
   e. Sensorium2 and Sensorium3?

Experimental Conditions

In this study all participants had to complete 6 different interventional conditions which were compared thereafter. Three of these conditions were different settings of the Sensorium while the other three conditions served as control conditions. We have chosen two meditative mental techniques as active controls; namely, a mindfulness meditation and a body scan exercise. Each of the 6 conditions lasted for about 20 min and is explained as follows:

Mindfulness Meditation (C1)

Mindfulness meditation as suggested by Ludwig and Kabat-Zinn (2008) asks the meditator to stay awake in the present moment without getting carried away by thoughts. Keeping the attention focused on their own breathing is expected to help the person stay in, or return to, the present moment. The mindfulness meditation session of 20 min duration was guided by a pre-recorded voice. Participants were first guided into relaxation and then instructed to observe their own breathing. During a quiet phase they were told to keep their attention to their breathing while mindfully staying in the present moment. As soon as they realized that thoughts came up carrying them away from the present moment, they had to calmly return their attention on their own breathing. This is essentially the task of mindfulness meditation as taught in MBSR training courses.

Sensorium1 (C2)

In the condition of Sensorium1 participants experienced their own heartbeat in the form of light and sound. Participants were instructed to just experience the sounds and light changes reflecting their own body processes without trying to manipulate or question them. This condition had some similarities to the experience in a mindfulness meditation. However, instead of focusing on breathing, which is normally perceived through bodily sensations, in the Sensorium1 condition the attentional focus was on the heartbeat perceived in the environment through the auditory and visual channels. As these senses do not usually perceive our heartbeat, the perception of them may lead to an extraordinary and intense experience. The ECG was fed back by alternating 7 different sonification styles and instruments as illustrated in Fig. 2a. The illumination presented the heart rate variability. Accelerated heart rates were shown as red lights and decelerated heart rates in blue. In contrast to the standard analysis of heart rate variability, this method did not analyze the spectrum of the heart rate but mapped the heart rate directly into colors.

Body Scan Exercise (C3)

A basic idea of the Sensorium was to provide an enhanced body experience through the presentation of body processes that under normal circumstances are not, or only very weakly, perceptible. A comparable non-technological mental technique was provided by the so-called body scan exercise. In this exercise the participant was asked to mentally concentrate on the sensation of various parts of their own body while sitting or lying down in a relaxed state. A pre-recorded voice guided the participants' attention through the physical body. By following the voice through the body, the body scan reduces tension and encourages acceptance of the moment. To enhance awareness of kinesthetic sensations, this exercise is done eyes closed. The body scan exercise in our study was similar to the body scan suggested by Ludwig and Kabat-Zinn (2008) in the MBSR training (Fjorback et al. 2011). Research suggests that the body scan increases the cardiac respiratory sinus arrhythmia and therefore enhances relaxation (Ditto et al. 2006). For conformity reasons with the other conditions of this study we had to shorten the original MBSR training body scan to about 20 min.

Sensorium2 (C4)

The setting of Sensorium2 included feedback of both ECG and EEG signals. During the whole phase the slow cortical potential shifts below 1 Hz were mapped to the red–blue color range. Negative brain potentials moved the color into reddish while positive shifts altered the color into bluish tones. For a short period of 2.5 min the green channel reflected the intensity of the current alpha oscillations. Sonification started with the ultra-slow cortical potentials and continued with increasing brain frequencies. The sonified signals and instruments altered as shown in the diagram in Fig. 2b. The phase ended with the relaxing feedback of the heartbeat together with slow cortical potential shifts. Participants were instructed to perceive their own body processes and just experience the sounds and light changes without trying to manipulate or question them. A pentatonic harmony guaranteed harmonic sound sequences.

Pseudo-Sensorium (C5)

The Pseudo-Sensorium was intended as a control condition. Participants were exposed to the same audiovisual settings compared to the setting of Sensorium3 as explained below. In contrast, however, the signals creating the stimulation did not originate from the participants themselves but came from a pre-recorded session of another test person. For conformity reasons the participants were instructed that they now were not perceiving their own signals and therefore should just enjoy the experience as an audiovisual relaxation exercise.

Sensorium3 (C6)

The condition of Sensorium3 was similar to that of Sensorium2. However, the setting of Sensorium3 contained a different sequence of sonifications and selections of instruments according to Fig. 2c. Again, pentatonic harmonies were chosen.

Experimental Design

Before the first session, all participants completed a basic questionnaire assessing personal data and exclusion criteria. Three additional questionnaires assessed body consciousness, mindfulness, and emotional exhaustion which are not reported here. Each participant had to complete all

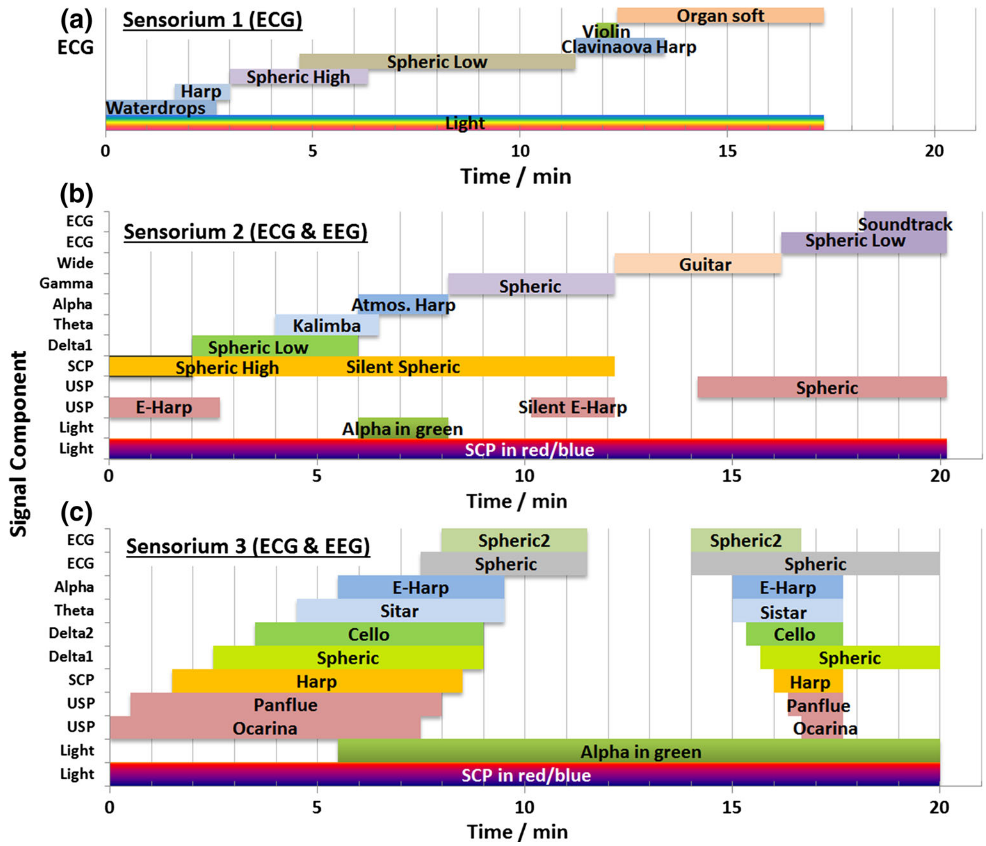

Fig. 2 The sequence of presented signals and the corresponding musical instruments is depicted for the three Sensorium sessions

6 different conditions in three daily sessions (Table 1). Each daily session consisted of two experimental phases. At the end of each session the participants were offered a debriefing phase of 10–20 min. Before a Sensorium session participants were instructed that all sounds and light changes were initiated by the ongoing signal of their heart or brain. They should not judge, think about the meaning, or try to manipulate these stimuli but just enjoy them from moment to moment.

Feedback Questionnaire

Feedback questions were categorized into 7 categories referring to the intervention phase, plus 2 final questions referring to the debriefing and the evaluation of the whole session. The first 3 question categories were named (1) *physical sensations* using 5 item pairs, (2) *emotional condition* using 6 item pairs, and (3) *mental state* using 3 item pairs. The remaining categories 4–9 had only one item each. Question categories and item pairs were the following:

1. Physical sensation: narrow–wide, weaker–more intensive, tense–relaxed, painful (uncomfortable)–more comfortable, powerless–empowered
2. Emotional condition: activated–calm, unbalanced–balanced, sadder–happier, unsatisfied–satisfied, anchorless–secure, dissociated–connected
3. Mental state: confused–clear, introverted–extroverted, empty–satisfied
4. Experience: ordinary–extraordinary
5. Motivation: tiring/demotivating–vitalizing/motivating
6. Duration: Phase was too short-too long
7. Could you notice a connection between yourself and the audiovisual perceptions?

Table 1 Experimental sequences of the two groups

	Session 1	Session 2	Session 3
Group 1	**C1**-FQ–**C2**-FQ–D	**C3**-FQ–**C4**-FQ–D	**C5**-FQ–**C6**-FQ–D
Group 2	**C2**-FQ–**C1**-FQ–D	**C4**-FQ–**C3**-FQ–D	**C6**-FQ–**C5**-FQ–D

C1 Mindfulness meditation, *C2* Sensorium1, *C3* Body scan exercise, *C4* Sensorium2, *C5* Pseudo-Sensorium, *C6* Sensorium3, FQ feedback questionnaire, *D* debriefing

8. The experience was irrelevant–relevant
9. The debriefing was irrelevant–helpful

The questions had to be answered on a scale from −3 to +3 with 0 meaning that no difference could be attributed to the corresponding category. In questions 4 and 7 we used a scale from 0 to +3. In the analysis we concentrated only on the first 6 question categories because category 7 could solely be applied to the Sensorium sessions and categories 8 and 9 referred to the debriefing.

Measurements

The Sensorium software recorded all signals measured by the NeXus-10 device and saved them into one data file. One electrode detected the EEG from CPz (international 10/20 system) referenced to linked mastoids. ECG was measured with one electrode at the sternum and one below the costal arch. The system was grounded on the right shoulder. Besides the two channels that were used as feedback signals, respiration and skin conductance (that is, the electrodermal activity, EDA) served as additional measures. Respiration was measured with a belt equipped with a stretch sensor; electrodermal activity was measured with two electrodes on the palm of the non-dominant hand.

Participants

There were 36 participants (15 male/21 female) between 21 and 69 years old ($M = 44$, $SD = 12$). 50 % of them played a musical instrument. 69 % liked listening to classical music, 42 % liked Jazz music, 64 % used to listen to Pop/Rock music, 50 % to relaxation music, and 42 % liked country music. Twenty-six participants (72 %) practiced meditation on a regular basis while ten (28 %) did not. On average, the 26 meditating participants had practiced for M = 8.2 years and meditated 3.1 times per week. Six participants (23 %) practiced mindfulness meditation, seven (28 %) Zen meditation, and three (11 %) autogenic training. People with epilepsy or psychological problems such as anxiety, depression, etc. were excluded from the study. Since one aim of the Sensorium was to provide a meditative tool of self-experience for people who are not used to meditation techniques, we decided to compare the results of meditating and non-meditating participants.

Data Analysis

Feedback Questionnaire

Since the question categories were formed freehand, an explorative factor analysis was calculated in order to investigate the latent constructs beyond the feedback questions. For this purpose the feedback questions' correlation matrix was used in the further analysis. Since categories 4 and 6 represent general evaluations of the conditions they were not included in this analysis. Thus, the initial extraction of 15 factors (equaling the number of items) results in 2 factors with an eigenvalue greater than 1 (Factor1: 8.44, Factor2: 1.54). According to the Kaiser-criterion, 2 factors have to be extracted in the further analysis. Using the Scree criterion it would be justifiable to extract 1 further factor with an eigenvalue <1 (0.834). Since we mainly formed 3 question categories beforehand, we decided to extract 3 factors for reasons of content. Those 3 factors accounted for 72.1 % of variance (Factor1: 56.24 %, Factor2: 10.27 %, Factor3: 5.56 %). The next factor would have offered an eigenvalue of 0.629 explaining additional 4.19 % of variance. After calculating specifically 3 factors through the exploratory factor analysis (the unrotated factor pattern is presented in Table 2) orthogonal rotation using the Varimax method was applied. An orthogonal rotation was preferred to an oblique rotation because it offered a sound simple structure. The orthogonally rotated factor structure (Table 2) shows 3 factors offering acceptable values of Cronbach's alpha and can be best described as follows:

1. *Well-being* ($\alpha = 0.93$, eigenvalue = 3.57)
   Can be best described as an emotional factor representing how comfortable a participant feels in a certain experimental condition
   6 Items: tense–relaxed, painful (uncomfortable)—more comfortable, activated–calm, unbalanced–balanced, anchorless–secure, confused–clear
2. *Perceptual changes* ($\alpha = 0.87$, eigenvalue 3.16)
   Can be best described as a perceptual factor representing changes and their intensity regarding one's own sensory perception in a certain experimental condition
   3 Items: narrow–wide, weaker–more intensive, dissociated–connected
3. *Life-spirit* ($\alpha = 0.83$, eigenvalue = 2.77)
   Can be best described as a motivational factor representing the vitality and pleasure perceived in a particular experimental condition
   6 Items: powerless–empowered, sadder–happier, unsatisfied–satisfied, introverted–extroverted, empty–fulfilled, tiring/demotivating–vitalizing/motivating

The items of each factor were then averaged and therefore merged into one value. Further, single items from the categories 4 and 6 were added as separate factors to the analysis resulting in 5 different dimensions for analysis, namely, well-being, perceptual changes, life-spirit, extraordinariness, and duration.

Table 2 Factor loadings of the rotated and unrotated matrix

Item	Rotated			Unrotated			Factor
	Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3	
Narrow–wide	0.41	**0.65**	0.14	0.71	−0.20	0.25	2
Weaker–more intensive	0.35	**0.77**	0.19	0.76	−0.16	0.38	2
Tense–relaxed	**0.59**	0.57	0.08	0.76	−0.31	0.08	1
Painful (uncomfortable)–more comfortable	**0.57**	0.52	0.29	0.82	−0.11	0.03	1
Powerless–empowered	0.23	0.42	**0.60**	0.68	0.34	0.13	3
Activated–calm	**0.80**	0.29	0.18	0.79	−0.26	−0.27	1
Unbalanced–balanced	**0.79**	0.38	0.27	0.87	−0.19	−0.20	1
Sadder–happier	0.33	0.35	**0.74**	0.77	0.42	0.00	3
Unsatisfied–satisfied	0.53	0.43	**0.59**	0.88	0.19	−0.05	3
Anchorless–secure	**0.53**	0.46	0.50	0.85	0.11	−0.01	1
Dissociated–connected	0.51	**0.60**	0.30	0.83	−0.10	0.14	2
Confused–clear	**0.51**	0.38	0.50	0.79	0.13	−0.06	1
Introverted–extroverted	−0.03	−0.14	**0.48**	0.12	0.46	−0.14	3
Empty–satisfied	0.26	0.17	**0.37**	0.45	0.17	−0.07	3
Tiring, demotivating–vitalizing, motivating	0.20	0.28	**0.55**	0.56	0.34	0.04	3

Bold values indicate the maximum loading which determines the assciation to a certain factor

Brain Physiology

EEG was sampled at 256 S/s in a frequency range from DC to 40 Hz. EEG data were detrended, filtered from 1 to 40 Hz, inspected for artifacts, and then transformed into frequency bins using the Welch transform as method for Fast Fourier Transformation (FFT). A sliding window of 2 s duration and one second overlap resulted in 60 FFT samples per minute and a frequency resolution of 0.5 Hz. Log-transformed squared FFT amplitudes reflect the power spectral density (PSD). As a consequence to the log-transform, PSD values can be negative. Frequency bins were averaged forming the predefined frequency bands: Delta (1–3.5 Hz), Theta1 (4–6.5 Hz), Theta2 (7–8.5 Hz), Alpha1 (9–10.5 Hz), Alpha2 (11–12 Hz), Beta1 (12.5–15 Hz), Beta2 (15.5–25 Hz), Gamma (25.5–40 Hz). Note that these frequency bands are different from those used in the feedback. For removal of high amplitude artifacts in the spectrum the whole recording period of about 20 min, all one second short-time FFT samples were averaged using median calculation. We excluded all samples which exceeded the median by 3 standard deviations. The session means and standard deviations of the cleaned spectrograms were calculated for further statistical analysis. For comparison of the EEG spectrum of the beginning with the end of a session, the means of FFT samples for each frequency band from the first 5 min were compared with the means of the final 5 min.

Respiration

Respiration rate was calculated after filtering the respiration signal in a range from 0.02 to 1 Hz. The median was used as averaging respiration rate over time.

Electrodermal Activity

The skin conductance response (SCR) as a component of the electrodermal activity is considered to have a frequency range between 0.016 (corresponding to a time constant of 10 s) and 1 Hz. The filtered signal then was differentiated and square-rooted. The mean square root provided a measure for the fluctuation in the EDA (SCR_rms). We were interested in the percentage of responses that were greater than two times the SCR_rms called p2_rms.

Heart Rate Variability

Heart rate (HR) was calculated through the peak-to-peak (RR)-intervals of the ECG signal. The HR was filtered into the HRV-typical frequency bands very low frequency (VLF, 0.003–0.04 Hz), low frequency (LF, 0.04–0.15 Hz), high frequency (HF, 0.15–0.4 Hz) (Task Force of The European Society of Cardiology and The North American Society of Pacing and Electrophysiology 1996). While the VLF band was found to be dominated by the sympathetic nervous system, the HF band is associated with parasympathetic activation. Artifact corrected RR beat-to-beat intervals are denoted with NN. The mean inter-beat interval was marked with NN_m. The ratio of those consecutive changes in HR differing more than 50 ms from each other divided by all changes was termed pNN50 which also provides a measure for the parasympathetic activation. The ratio between LF and HF (R_LH) is regarded as the vegetative balance between parasympathetic and sympathetic nervous system (Malik 1996).

Table 3 Non-inferiority test with delta = 0.2

W	Sensorium1–Meditation	Sensorium2–Bodyscan	Sensorium3–Pseudosensorium	Sensorium3–Sensorium2
Well-being	2.07*	2.78**	5.82**	3.25**
Perceptual changes	2.34**	2.37**	6.54**	4.04**
Life spirit	3.58**	2.89**	4.40**	3.33**
Extraordinariness	6.50**	7.02**	5.46**	3.64**
Duration	4.03**	2.66**	8.75**	5.61**

Asterisks indicate p values after FDR adjustment across 5 rating dimensions and 4 comparisons

* $p < 0.05$; ** $p < 0.01$

Statistical Data Analysis

With respect to our hypotheses and questions H1 to H5 different methods for analysis were used. However, as the normal distribution was not fulfilled for all parameters we chose non-parametric tests. While the first three hypotheses refer to the subjective feedback ratings, H4 and H5 refer to the electrophysiological data.

H1 The results of the feedback questionnaires from the 6 different conditions were compared using the non-parametric Wilcoxon signed-rank test.

H2 For testing non-inferiority we used an approach that was described by Munzel and Hauschke (2003). A maximum irrelevant difference delta = 0.2 was used as suggested to be reasonable by Wellek and Hampel (1999).

H3 The difference in subjective feedback ratings between meditating and non-meditating participants was answered with a Mann–Whitney U test comparing 26 meditating to 10 non-meditating participants.

Question H4 asked for the physiological changes during each intervention. We compared the first 5 min of a condition's physiological data to its final 5 min using a Wilcoxon signed-rank test. The 8 EEG frequency bands, 6 HRV measures, one EDA measure, and one respiration measure, formed a data set of 16 parameters.

Question H5 was answered by first averaging the activities of each measure within the whole intervention period of a session for each participant. A Wilcoxon signed-rank test served as statistical method for comparing the means of all 36 participants between conditions. We compared the two conditions of each session with each other as well as Sensorium2 and Sensorium3.

Correction for Multiple Testing

Based on the algorithms of Benjamini and Hochberg (1995), we applied a correction to account for false positives in the statistical significances to all physiological tests (Yekutieli and Benjamini 1999). The whole matrices of Tables 3, 4 and 6 were used for the correction of probability values.

Results

Subjective Feedback Ratings (H1 and H2)

Feedback ratings of 36 participants reflect the subjective changes after each of the six interventional conditions. We focused on the 5 dimensions well-being, perceptual changes, life-spirit, extraordinariness, and duration as reported above. Figure 3 illustrates these results and indicates the significances resulting from a Wilcoxon signed rank test. Improvements in the 'well-being' and 'perceptual changes' factors can be noticed in all conditions. However, the Pseudo-Sensorium's changes were significantly lower compared to almost all other conditions. Regarding the factor 'life-spirit' all conditions presented positive improvements without differing significantly from each other. Compared to the Non-Sensorium conditions, the uniqueness (extraordinariness scale) of the Sensorium experience was rated significantly higher with the exception of the comparison between the Pseudo-Sensorium and both Sensorium1 and Sensorium2 which did not significantly differ. Expressed in numbers, 29–32 of the 36 participants rated the Sensorium conditions' experiences as extraordinary while 18/36 rated the meditation session and 20/36 rated the body scan session as extraordinary. Finally, the duration of the Pseudo-Sensorium was rated as too long and therefore differs significantly from all other conditions. Sensorium3 was rated as too short in duration which is highly significantly different to mindfulness meditation, the Pseudo-Sensorium, and Sensorium2.

In the pairwise comparison between consecutive conditions Sensorium1 and mindfulness meditation no significant differences were found except in the extraordinariness factor. Also the Sensorium2 only differed significantly from body scan in the extraordinariness factor. This asks for a non-inferiority test.

Table 4 *Z* values of intra-session changes within each condition of EEG power spectra and 8 peripheral physiological variables averaged across 36 participants

Physiol. measure	Band/ measure	C1: Meditation	C2: Sensorium1	C3: Body scan	C4: Sensorium2	C5: Pseudo-Sensorium	C6: Sensorium3	Non-Sensorium	Sensorium
EEG	Delta	−0.46	1.02	2.11	2.06	1.37	2.53**	1.78	3.27**
	Theta1	0.25	1.51	2.18	2.58*	2.40*	3.20**	2.93**	4.29**
	Theta2	2.06	4.18**	0.83	3.05**	3.38**	4.02**	3.75**	6.50**
	Alpha1	2.42*	4.19**	−2.62*	3.91**	3.38**	4.32**	1.62	7.23**
	Alpha2	3.14**	3.68**	−0.75	4.41**	3.72**	4.43**	3.61**	7.28**
	Beta1	2.61*	2.75*	0.77	3.99**	3.55**	4.04**	3.98**	6.33**
	Beta2	3.00**	1.12	−1.57	2.99**	3.17**	3.11**	2.49*	4.00**
	Gamma	2.86*	−0.53	−1.51	0.82	1.34	1.45	1.50	0.96
HRV	VLF	1.67	−0.28	2.41*	3.33**	3.39**	0.97	4.35**	2.24**
	LF	0.06	−1.81	2.11	2.07	1.62	0.47	2.14	0.28
	HF	1.49	−1.08	2.18	2.17	−0.03	0.06	2.20	0.61
	R_LH	−0.22	−0.25	0.52	0.19	1.39	−0.28	0.83	−0.18
	NN_m	0.02	−1.60	2.47*	2.99**	1.66	1.46	2.51*	1.93
	pNN50	0.40	−1.38	1.16	1.61	0.23	−0.42	1.02	−0.30
EDA	p2_rms	−2.02	−0.49	1.24	−0.84	1.08	−0.31	0.17	−0.99
Respiration	M	0.02	3.27**	0.44	1.51	0.46	2.62*	0.45	4.31**

The initial 5 min and final 5 min of a session were compared using Wilcoxons signed-rank test. Positive values reflect increasing values from beginning to end of a session

Non-Sensorium C1 + C3 + C5, *Sensorium* C2 + C4 + C6

Asterisks indicate *p* values calculated after FDR adjustment across 9 EEG frequency bands and 8 peripheral physiological parameters

* $p < 0.05$; ** $p < 0.01$. Positive *z* values reflect increases of PSD during the session

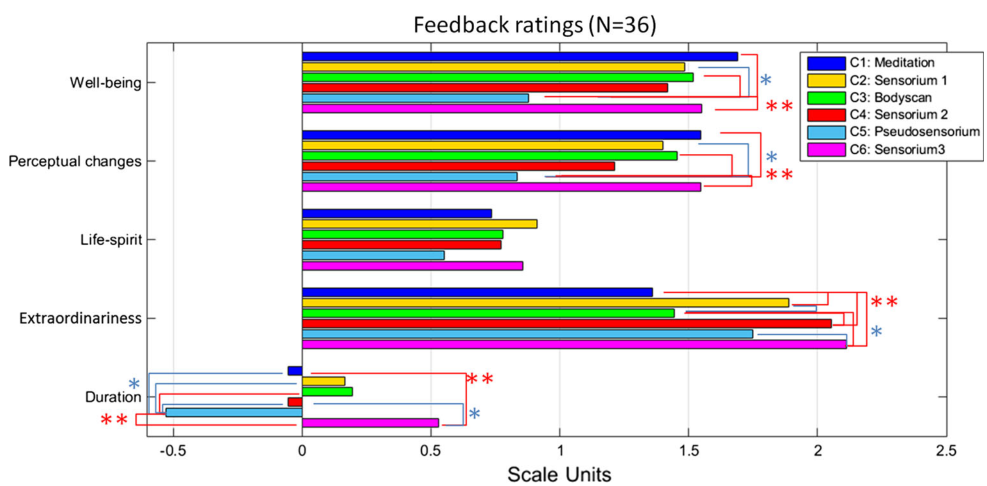

Fig. 3 The mean feedback ratings after each of the 6 conditions is displayed for each factor. The results of the Wilcoxon signed rank test are shown with bracket lines indicating the significant differences. In *blue* $p < 0.05$* and in *red* $p < 0.01$**

With respect to H1 we can conclude that significances were found between Sensorium and Non-Sensorium interventions. The second assumption of finding differences between Sensorium1, 2, and 3 could not be confirmed for the factors well-being, perceptual changes, life-spirit, and extraordinariness. Here only Sensorium 3 was rated as too short compared to Sensorium2.

In the non-inferiority test all rating values were significant for the four comparisons (see Table 3), thus the Sensorium1 was not inferior to mindfulness meditation on the scales of well-being, perceptual changes, life-spirit, extraordinariness, and duration. As well, the Sensorium2 was not inferior to the body scan exercise, Sensorium3 was not inferior to the Pseudo-Sensorium, and Sensorium3 was not inferior to Sensorium2. However, testing the reverse contrast showed that non-inferiority could not be corroborated for Sensorium2 compared to Senosrium3 in the dimensions perceptual changes and duration. The Pseudo-

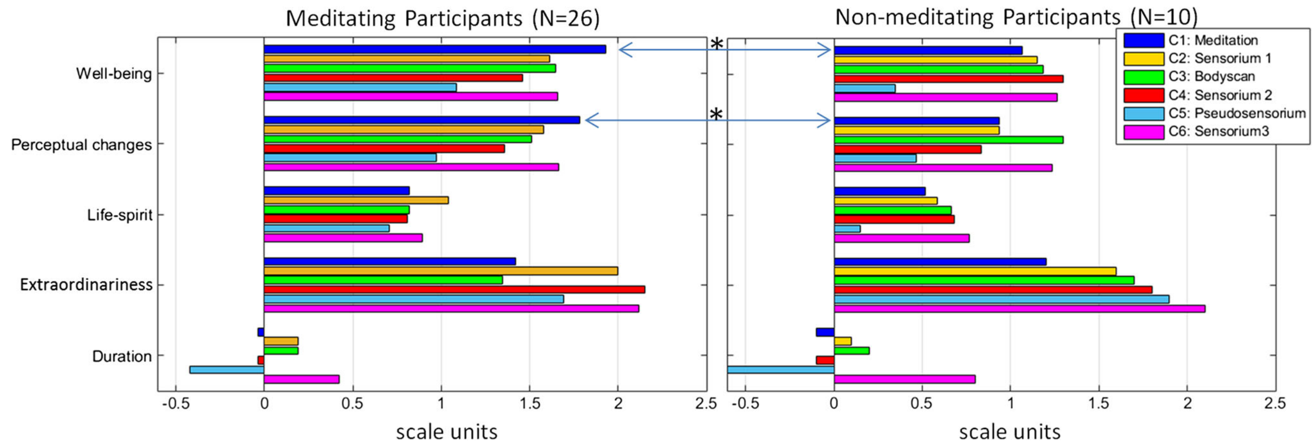

Fig. 4 Means of feedback self-ratings are displayed for all conditions separately for meditating and non-meditating participants

Sensorium failed non-inferiority in all 5 dimensions confirming H2c). Thus, the hypothesis H2 stating that the Sensorium interventions are not rated worse compared to the active control conditions was confirmed.

Group Comparisons (H3)

Comparisons between meditating and non-meditating participants were conducted using a Mann–Whitney-*U* test on the data of the subjective feedback ratings to answer the research question whether meditating or non-meditating participants would profit more from the Sensorium (Fig. 4). Significant differences are offered by the condition of mindfulness meditation in which meditating participants rated their well-being ($z = 2.18$, $p < 0.05$) as more increased and perceived perceptual changes ($z = 2.28$, $p < 0.05$) higher than non-meditating participants. All other comparisons between those two groups yield no significant differences.

Physiological Comparisons Within Conditions (H4)

Brain Physiological Changes

The EEG power spectral changes during a session are shown in Table 4 for each condition. Taken together all the Sensorium conditions showed significant increases of PSD in most frequency bands ($z >= 2.53$; $p < 0.05$) except Gamma which showed a non-significant increase. Sensorium1 offered significant increases of PSD regarding Theta2 ($z = 4.18$; $p < 0.01$), the entire alpha frequency band ($z >= 3.68$; $p < 0.01$), and Beta1 ($z = 2.75$; $p < 0.05$). These were the frequency bands demonstrating the most significant positive *z* values >6 in the overall Sensorium condition which corresponds to an increase in PSD by factor 1.4 in the Alpha1 band and 1.3 in Theta2 and Alpha2.

Looking at the overall Non-Sensorium conditions, there were significant increases of PSD in the entire theta, beta, and alpha frequency bands. In those bands PSD increased by factors around 1.1–1.2 when significant. The Pseudo-Sensorium showed highly significant increases of PSD similar to Sensorium2 and 3 ($z >= 2.40$; $p < 0.05$). The body scan condition offered its only significant *z* value with respect to Alpha1 ($z = -2.62$, $p < 0.05$) which is negative and therefore represents the only significant decrease of PSD in all comparisons. Mindfulness meditation showed significant increases in PSD in the alpha and beta bands as well as in Gamma ($z >= 2.86$, $p < 0.05$).

Figure 5 provides an overview of changes regarding the standardized mean spectral power values so that conditions can be compared within each frequency band. Despite of the high significances in this field with $p < 0.01$, the effect sizes, conceptualized as standardized mean differences (Cohen's d), were only in the range of 0.15 to 0.30. Increases in Gamma during mindfulness meditation reached an effect size of $d = 0.69$ ($z = 2.86$, $p < 0.01$).

When comparing all Sensorium conditions together with all non-Sensorium conditions a significantly stronger increase of PSD in Theta2 ($z = 2.57$, $p > 0.05$), Alpha1 ($z = 4.26$, $p < 0.01$) Alpha2 ($z = 2.71$, $p < 0.05$) could be observed in the Sensorium conditions.

Changes in HRV, Respiration, and EDA

Table 4 also offers the results for changes in HRV, Respiration and EDA over the course of each of the conditions. Regarding HRV significant increases in the mean NN intervals (NN_m, which is the inverse heart rate) during the body scan condition, the overall non-Sensorium conditions as well as Sensorium2 can be noticed. In other words, the body scan lowered the heart rate by 1.4 beats per minute and the Sensorium by 1.5 beats per minute. The very slow frequencies of the HRV increased in the body scan but

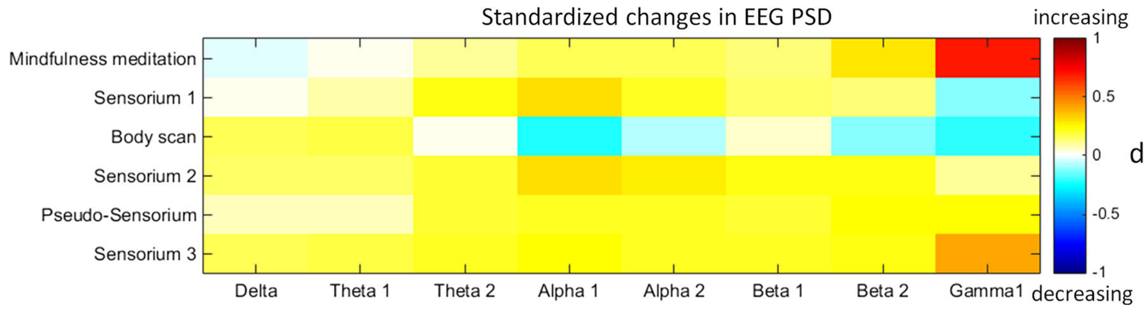

Fig. 5 Changes in standardized mean EEG spectral power. PSD measures of each EEG band during the first 5 min and final 5 min of a phase averaged across time, subtracted, divided by their standard deviations, and averaged across participants

Table 5 Mean amplitudes of EEG power spectral density and mean values for 8 peripheral physiological variables across all six conditions

Physiol. measure	Band/ measure	C1: Meditation	C2: Sensorium1	C3: Body scan	C4: Sensorium2	C5: Pseudo-Sensorium	C6: Sensorium3
EEG log(μV^2/Hz)	Delta	0.66	0.67	0.66	0.61	0.68	0.64
	Theta1	0.23	0.21	0.26	0.18	0.25	0.21
	Theta2	0.31	0.25	0.35	0.20	0.26	0.25
	Alpha1	0.40	0.31	0.49	0.22	0.28	0.27
	Alpha2	0.20	0.15	0.22	0.07	0.13	0.11
	Beta1	−0.05	−0.08	−0.08	−0.14	−0.10	−0.12
	Beta2	−0.26	−0.28	−0.32	−0.35	−0.34	−0.36
	Gamma	−0.78	−0.79	−1.01	−0.93	−0.95	−0.97
HRV	VLF (ms^2)	687.30	722.96	706.12	667.07	784.40	786.61
	LF (ms^2)	1631.43	1395.91	1032.97	1034.26	1080.42	1151.14
	HF (ms^2)	568.90	492.08	574.48	551.34	681.13	552.53
	R_LH	3.85	3.68	2.54	2.92	2.84	2.79
	NN_m (ms)	852.59	846.52	914.68	905.27	885.98	890.06
	pNN50 (%)	6.52	5.51	7.46	7.42	6.55	7.11
EDA	p2_rms (%)	3.67	3.94	2.83	3.33	3.22	3.40
Respiration	M (1/min)	10.05	11.93	14.37	13.74	15.38	14.03

even more in Sensorium2 and Pseudo-Sensorium sessions. No changes were observed with regard to the skin conductance responses (p2_rms). Respiration rates increased significantly during the Sensorium1 session by 1.5 per minute ($z = 3.27$, $p < 0.01$) and duringSensorium3 by 1.8 per minute ($z = 2.62$, $p < 0.05$) and thus in the overall Sensorium conditions. There were no other significant differences after adjustments were made to account for false discovery results (FDR), which was necessary due to the large number of comparisons being calculated.

Comparing all Sensorium conditions with all non-Sensorium conditions resulted in a highly significant increase in the respiration rate ($z = 4.22$, $p < 0.01$). The increase of the HF component of the HRV in Non-Sensorium sessions also reached significance with $z = 2.61$ ($p < 0.05$).

Physiological Comparisons Between Conditions (H5)

An overview of mean amplitudes during each condition is given in Table 5.

Comparisons Between Sensorium and Non-Sensorium Conditions (H5a)

These results are visible in the right column of Table 6. Regarding the mean EEG PSD within each condition the Sensorium conditions offered significantly lower PSD in all frequency bands except for Gamma, which showed slightly, but not significantly, higher power during non-Sensorium conditions. For Delta and Beta2 the significance level was $p < 0.05$ and for the other frequency ranges it was $p < 0.01$.

Table 6 *Z* values of comparisons between conditions for EEG power spectra and 8 peripheral physiological variables of all 36 participants using Wilcoxons signed-rank test

Physiol. measure	Band/ Measure	Sensorium1–Meditation	Sensorium2–Body scan	Sensorium3–Pseudo-Sensorium	Sensorium3–Sensorium2	Sensorium–non-Sensorium
EEG	Delta	0.49	−2.23	−2.09	1.46	−2.39*
	Theta1	−2.26	−4.19**	−2.48	1.81	−5.33**
	Theta2	−2.95*	−4.84**	−0.41	2.28	−5.10**
	Alpha 1	−3.36**	−5.03**	−0.74	2.22	−5.90**
	Alpha 2	−2.25	−5.07**	−1.48	1.62	−5.43**
	Beta 1	−1.84	−2.70*	−0.86	1.10	−3.20**
	Beta 2	−1.63	−1.74	−0.68	−0.08	−2.42*
	Gamma	−0.11	1.98	0.03	−1.74	1.05
HRV	VLF	0.00	0.00	0.28	0.82	0.06
	LF	−1.35	1.03	1.05	0.58	0.32
	HF	−1.56	−0.38	1.70	−0.14	0.19
	R_LH	−0.72	0.88	−0.03	0.58	0.27
	NN_m	0.01	−0.52	0.82	−0.60	0.08
	pNN50	−1.19	−0.21	0.22	−0.46	−0.32
EDA	p2_rms	1.05	1.65	0.49	0.58	1.92
Respiration	M	3.41**	−1.35	−2.69*	0.87	0.13

Asterisks indicate p values calculated after FDR adjustment across the whole matrix

* $p < 0.05$; ** $p < 0.01$

Brain physiological Comparisons (H5b-e)

Table 6 shows the results of comparisons of 3 selected Sensorium and Non-Sensorium conditions plus one comparison between Sensorium2 and 3 whereas Fig. 6 indicates the effect sizes of these comparisons.

Sensorium1 offered significantly lower power inTheta2 and Alpha1 compared to mindfulness meditation. Sensorium2 offered significantly lower PSD in the Theta, Alpha, and the Beta1bands. PSD in Alpha1 was at average 1.6 times higher in the body scan exercise compared to the corresponding Sensorium2 session. Differences between Sensorium3 and Pseudo-Sensorium were not significant. As well, there were no significant differences between Sensorium2 and 3. Thus, in the Sensorium sessions participants had a significantly lower EEG power in all frequency bands (except for Gamma) compared to non-Sensorium sessions.

Comparisons in HRV, Respiration, and EDA

As presented in Table 6 HRV and EDA measures did not show significant differences between conditions. Compared to mindfulness meditation significantly higher respiration rates were observed in Sensorium1 ($z = 3.41$, $p < 0.01$). At average, participants had 1.9 breathing cycles per minute more in the Sensorium1. In Pseudo-Sensorium they had about 1.4 cycles more than in the corresponding Sensorium3 ($z = -2.69$, $p < 0.05$).

Discussion

Hypotheses H1 and H2. Several differences in the subjective measures could be found between the six conditions. Most of the differences related to the Pseudo-Sensorium, which was rated as significantly less positive in questions related to well-being and perceptual changes. The Pseudo-Sensorium itself provided an extraordinary experience which can be derived by the result that the Pseudo-Sensorium was not significantly different in extraordinariness than the Sensorium2. Participants rather rejected the Pseudo-Sensorium by rating its duration as too long while the Sensorium3 setting was rated as too short indicating that participants would have preferred a longer period of true feedback. In fact, 16/36 participants rated the Pseudo-Sensorium as too long and only 4/36 as too short. In contrast after the corresponding Sensorium3 session 18/36 wished the session to be longer and only 3/36 rated it as being too long. These results suggest, as hypothesized in H2c, that a real and honest feedback of the signals is essential for the successful implementation of the Sensorium approach.

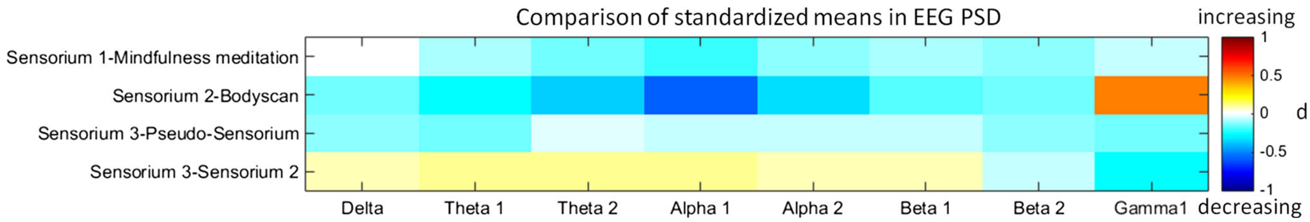

Fig. 6 Comparisons of standardized mean values of each EEG band between conditions are displayed. Values of each EEG band were averaged across participants and time. Then, means of all conditions in each frequency band were standardized resulting in relative PSD values which then were compared between conditions using the formula of Cohen's d

Sensorium1 was intended to be a kind of heart-mindfulness meditation. This was compared with a mindfulness meditation that asked to be mindful on the breathing. As no differences and no inferiority in any of the rating factors were found we conclude that from this perspective the Sensorium was not inferior to the meditation confirming hypothesis H2a. Likewise, H2b can be accepted which asked for non-inferiority of Sensorium2 providing feedback of heart and brain signals in comparison with the body scan. Therefore, it can clearly be stated that the Sensorium seems to be equivalent to the two mindfulness techniques with respect to subjective ratings of the experiences.

Non-inferiority with respect to all subjective ratings also was found for Sensorium3 in contrast to Sensorium2 confirming hypothesis H2d. Sensorium3 could even be considered to be more favorable because all means exceeded those of Sensorium2 and the duration was significantly more positive which we interpret as people wished to have more of it. Thus, with respect to the subjective feedback ratings, the first and the second hypothesis could be confirmed.

Hypothesis H3. Comparing meditating with non-meditating participants showed that mindfulness meditation had significantly less impact on positive 'well-being' and 'perceptual changes' in non-meditating participants. In contrast, the Sensorium sessions were only non-significantly less effective in the non-meditators compared to the meditating participants. With respect to our hypothesis, we could not verify that non-meditating participants profit more from the Sensorium sessions than meditating participants. However, as people without meditation experience profited less from a mindfulness meditation session, the Sensorium might be an approach that is more suitable for non-meditators than mindfulness meditation. The other conclusion that might be drawn from these data is that meditation has more powerful effects when it has been practiced long-term as compared to the effects experienced during an initial session of meditation.

Research question H4. The physiological signals were evaluated in an exploratory manner. The intra-session comparisons between initial and final 5 min within each condition should reflect the physiological changes evoked by the condition. However, as we did not record a baseline immediately before each session, pre-post comparisons were not possible which would have been better. In case the intervention had altered the physiological state rapidly during the first 5 min, this effect would not have been visible in our comparisons. Despite this limitation all Sensorium conditions showed highly significant increases in the activity of most EEG frequency bands over the centro-parietal cortex when the EEG activity during the last 5 min was compared to the first 5 min. This increase was predominantly strong in the high Theta, Alpha, and Beta1 bands. These rhythms are mainly related to resting state activity indicating that the Sensorium supports these rhythms more than meditation or body scan exercises. Beta1 constitutes the frequency band associated with the sensory motor rhythm and showed significant increases in all conditions except the body scan condition. Actually, increases in Beta1 indicate an idling sensory motor rhythm that is associated with decreased sensory input and decreased motor output, though this is not as well reflected in measurements from electrode position CPz as it would be at Cz, C3 and C4, which are more directly over the sensory motor area. This area is rather associated with sensory or movement processing. Increases in the Beta2 frequency band regarding the central-posterior area could be found during the conditions of the Sensorium2 and 3 suggesting an increased mental activation possibly related to the spatial processing of sound and light stimuli. With respect to Gamma activity the only significant increase was observed in the mindfulness meditation. Increases in Gamma are usually associated with transcendental states of consciousness (e.g. Cahn et al. 2010). The only significant change in the body scan condition constituted a decrease in Alpha1, perhaps reflecting a decrease in relaxation while conducting the body scan exercise.

Another plausible explanation for the changes during the Body Scan exercise, based upon the fact that this was the only exercise done with eyes closed, is that the decrease in Alpha1 and increases in the slower frequencies in the last 5 min of a 20-min session suggests that the subjects may have been falling asleep. Reinforcing that possibility is the fact that electrodermal activity was lowest during the body scan condition.

The increasing activity in the very low frequencies of the HRV have to be taken with care as most of the frequencies in this band were slower than the 5 min window. This might lead to inconsistent results. However, when taken seriously this would suggest that the Sensorium2 and the Pseudo-Sensorium had activated the sympathetic nervous system. A stimulating effect of Sensorium1 and Sensorium3 could also be expressed by increasing respiration rates.

Research question H5. One of the most prominent findings when comparing the mean PSD of the EEG of related conditions with each other was an increased Alpha1 in the meditation and the body scan exercises. This is a plausible result that can be explained with alpha blocking in conditions with open eyes. During the Sensorium session participants kept their eyes mostly open due to the visual stimulation. During meditation people should keep their eyes open but stared to the neutral white wall. During the body scan participants kept their eyes closed. Therefore, the highest values could be observed in the body scan, the second highest in the meditation session and lower values in the Sensorium sessions. Another major finding was that the session means of Sensorium sessions in almost all EEG bands showed lower power than in non-Sensorium sessions. This suggests that the Sensorium in general leads to a relatively strong decrease of EEG power (Tables 4, 5) which is slightly increasing during the session as shown in Table 3. This is plausible as the Sensorium stimuli first challenge the audiovisual system leading to a decrease in resting rhythms. The increasing activity might then reflect a habituation process. The most prominent effects in the EEG could be seen in the Sensorium3 session. The broad band decrease in EEG power as visible in the Sensorium sessions was also found in meditators who tried to get into states of thoughtless emptiness (Hinterberger et al. 2014). Our data therefore support the Sensorium in its meditative quality as compared to the meditative techniques used in this research that involved listening to scripts that guided the meditation. Interpretations of EEG power spectral data with respect to meditation, however, are limited due to the various contradictory study findings (Cahn and Polich 2006). There was no significant difference when comparing the Pseudo-Sensorium to Sensorium3. Therefore, we have to conclude that the alterations in neurophysiological states might be a function of the feedback stimulation and setting rather than a function of the subjective experience reported in the questionnaire ratings. As described, the subjective feedback ratings pointed out the superiority of Sensorium conditions with regard to the Pseudo-Sensorium.

The manifold significant differences as found in the EEG could not be observed in the HRV, EDA, and respiration data. A slightly but non-significant higher EDA response in the Sensorium sessions indicates a tendency towards a higher affective effect. During the body scan and during the Sensorium2 session the heart rate significantly decreased suggesting a relaxation response. In contrast, increasing respiration rates during Sensorium1 sessions contradict this finding.

To conclude, our study demonstrates that with respect to the mindfulness interventions used as active controls the Sensorium can be regarded as a comparable or even more powerful tool for gaining well-being and experiencing perceptual changes. Although in terms of well-being and perceptual changes persons with a meditative background seem to benefit slightly more from all of the 6 tested interventions, the Sensorium can be regarded as a preferred alternative for people without meditation experience. Future studies would have to focus especially on the role of the feedback mechanism in the Sensorium conditions and the contradicting data concerning increases or decreases in relaxing and stimulating effects. Further, we intend to perform a clinical trial which would show the effect on patients with clinical symptoms such as depression, anxiety, or eating disorders.

Acknowledgments The authors thank the BIAL Foundation (Portugal) and the Heiligenfeld Kliniken (Bad Kissingen, Germany) for their support of this research.

References

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society: Series B (Methodological), 57*(1), 289–300. doi:10.2307/2346101.

Birbaumer, N., Ghanayim, N., Hinterberger, T., Iversen, I., Kotchoubey, B., Kübler, A., et al. (1999). A spelling device for the paralysed. *Nature, 398*(6725), 297–298. doi:10.1038/18581.

Cahn, B. R., Delorme, A., & Polich, J. (2010). Occipital gamma activation during vipassana meditation. *Cognitive Processing, 11*, 39–56. doi:10.1007/s10339-009-0352-1.

Cahn, B. R., & Polich, J. (2006). Meditation states and traits: EEG, ERP, and neuroimaging studies. *Psychological Bulletin, 132*(2), 180–211. doi:10.1037/0033-2909.132.2.180.

Carmody, J., & Baer, R. A. (2008). Relationships between mindfulness practice and levels of mindfulness, medical and psychological symptoms and well-being in a mindfulness-based stress reduction program. *Journal of Behavioral Medicine, 31*(1), 23–33. doi:10.1007/s10865-007-9130-7.

Ditto, B., Eclache, M., & Goldman, N. (2006). Short-term autonomic and cardiovascular effects of mindfulness body scan meditation. *Annals of Behavioral Medicine, 32*(3), 227–234. doi:10.1207/s15324796abm3203_9.

Fjorback, L. O., Arendt, M., Ornbøl, E., Fink, P., & Walach, H. (2011). Mindfulness-based stress reduction and mindfulness-based cognitive therapy: A systematic review of randomized controlled trials. *Acta Psychiatrica Scandinavica, 124*(2), 102–119. doi:10.1111/j.1600-0447.2011.01704.x.

Hinterberger, T. (2007). Orchestral sonification of brain signals and its applications to brain-computer interfaces and performing arts. In *Proceedings of the 2nd international workshop on interactive sonification, York, UK, 3 February, 2007.*

Hinterberger, T. (2011). The Sensorium: A multimodal neurofeedback environment. *Advances in Human-Computer Interaction, 3*, 1–10.

Hinterberger, T., & Baier, G. (2005). POSER: Parametric orchestral sonification of EEG in real-time for the self-regulation of brain states. *IEEE Multimedia, 12*(2), 70–79.

Hinterberger, T., Mellinger, J., & Birbaumer, N. (2003). The thought translation device: Structure of a multimodal brain-computer communication system. In *Proceedings of the 1st International IEEE EMBS Conference on Neural Engineering, Capri Island, Italy, 20–22 March, 2003* (S. 603–606).

Hinterberger, T., Neuman, N., Pham, M., Kübler, A., Grether, A., Hofmayer, N., et al. (2004). A multimodal brain-based feedback and communication system. *Experimental Brain Research, 154*, 521–526.

Hinterberger, T., Schmidt, S., Kamei, T., & Walach, H. (2014). Decreased electrophysiological activity represents the conscious state of emptiness in meditation. *Frontiers in Psychology, 99*, 1–14. doi:10.3389/fpsyg.2014.00099.

Jacobson, E. (1938). *Progressive relaxation* (2nd ed.). Oxford: University of Chicago Press.

Ludwig, D. S., & Kabat-Zinn, J. (2008). Mindfulness in medicine. *JAMA, 300*(11), 1350–1352. doi:10.1001/jama.300.11.1350.

Malik, M. (1996). Heart rate variability. *Annals of Noninvasive Electrocardiology, 1*(2), 151–181. doi:10.1111/j.1542-474X.1996.tb00275.x.

Malinowski, P. (2008). Mindfulness as psychological dimension: Concepts and applications. *Irish Journal of Psychology, 29*(1), 155–166.

Malinowski, P. (2013). Neural mechanisms of attentional control in mindfulness meditation. *Frontiers in Neuroscience, 7*, 8. doi:10.3389/fnins.2013.00008.

Munzel, U., & Hauschke, D. (2003). A nonparametric test for proving non-inferiority in clinical trials with ordered categorical data. *Pharmaceutical Statistics, 2*, 31–37. doi:10.1002/pst.017.

Stetter, F., & Kupper, S. (2002). Autogenetic training: A meta-analysis of clinical outcome studies. *Applied Psychophysiology and Biofeedback, 27*(1), 45–98. doi:10.1023/A:1014576505223.

Task Force of The European Society of Cardiology and The North American Society of Pacing and Electrophysiology. (1996). Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. *European Heart Journal, 17*(3), 354–381.

Thompson, M., & Thompson, L. (2007). Neurofeedback for stress management. In Paul M. Lehrer, Robert L. Woolfolk, & Wesley E. Sime (Eds.), *Principles and practices of stress management* (pp. 249–287). New York: Guilford Press.

Wellek, S., & Hampel, B. (1999). A distribution-free two-sample equivalence test allowing for tied observations. *Biometrical Journal, 41*, 171–186.

Yekutieli, D., & Benjamini, Y. (1999). Resampling-based false discovery rate controlling multiple test procedures for correlated test statistics. *Journal of Statistical Planning and Inference, 82*(1), 171–196.