

Meditation in the third-person perspective modulates minimal self and heartbeat-evoked potentials

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ABSTRACT

Experienced meditation practitioners often report altered states of their sense of self, including decentering and distancing the self from the body and one's current concerns. Altered states of the sense of self, such as disembodiment and distancing of the self from the body, have also been induced experimentally using virtual reality (VR) and linked neurally to heartbeat-evoked potentials (HEPs). Whereas studies investigated the related neural correlates of such decentering during meditation, none experimentally modulated the sense of self during meditation practice using VR nor determined the potentially associated behavioral changes of the sense of self. Here we determined HEPs and behavioral measures in 23 participants who performed a guided meditation in VR, either from a third-person (3PP) or first-person perspective (1PP) to modulate the sense of self. In the 3PP-vs-1PP meditation condition, we report immediate effects including stronger sensations of detachment and disconnection, reduced salience of the perceived body boundary, and reduced self-identification with the body. HEP analysis revealed a more negative HEP amplitude in the 3PP condition, associated with activation of the posterior cingulate cortex and medial prefrontal cortex. Leveraging a new VR-supported meditation platform and methods, these data link the sense of self in meditation practice to the neuroscience of the bodily self, based on short-term subjective, behavioral, and neural changes. The study provides a foundation for future research on whether manipulating the minimal self in VR can aid in cultivating self-transcendent experiences reported by experienced meditators and whether integrating this manipulation facilitates the cultivation of long-term changes.

1. Introduction

Inquiring about the nature of the self is a fundamental part of many contemplative traditions (i.e., Albahari, 2006; Dahl et al., 2015; Hölzel et al., 2011; Kessel et al., 2016; Siderits et al., 2011; Tang et al., 2015). Heightened focus on the self in daily life (i.e., self-related thoughts, autobiographical memories, personal goals, mental time travel), has been criticized by these traditions and argued to lead to psychological distress (Dahl et al., 2015; Nikitin and Freund, 2021; Vago and Silbersweig, 2012) and meditation practitioners are often guided to distance and detach themselves from their conscious experience and self-related cognitive activities. Several contemplative practices encourage practitioners to take a distanced and de-centered perspective and to remain as a non-judgmental observer of ongoing fluctuating conscious experience (Dahl et al., 2015; Hölzel et al., 2011; Kessel et al., 2016; Millière et al., 2018), which often concerns the practitioners' body

and/or breath (Anālayo, 2019; Brandmeyer and Delorme, 2018; Tang et al., 2015).

Research in cognitive neuroscience also investigated perspective taking and resonates with this dichotomy between higher-level self-rated cognitions versus lower-level bodily perceptions, distinguishing two main forms of self-consciousness: a narrative self and a minimal (bodily) self (Damasio, 1999; Gallagher, 2000; Legrand and Ruby, 2009; Millière et al., 2018; Northoff et al., 2006; Seth and Tsakiris, 2018). The narrative self refers to a higher-level cognitive self, involving self-related thoughts, language and autobiographical memories, that shape our life narrative and core self-related beliefs. The minimal self, instead, is not extended in time and centers on conscious bodily experiences such as body ownership and self-identification with the body, based on multisensory perception. The minimal self can be altered experimentally, leading to changes in body ownership and self-identification through the manipulation of specific multisensory bodily signals (Blanke et al., 2015;

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Park and Blanke, 2019). In such multisensory paradigms using virtual reality (VR) (Bayer et al., 2023; Ehrsson, 2007; Lenggenhager et al., 2007; Noel et al., 2015; Salomon et al., 2016), participants receive touches on their backs while viewing an avatar from a third-person perspective (3PP; seen from behind and projected in front of them and receiving the same tactile stimulation), inducing illusory self-identification with the avatar.

Whereas, the narrative self and related processes have been studied in meditation (i.e., Britton et al., 2021; Farb et al., 2007; Vago and Zeidan, 2016), only a few researchers studied the role of the minimal self in meditation and how it depends on multisensory bodily mechanisms and a de-centered 3PP. Based on in-depth interviews of long-term meditators, it was reported that mindfulness meditation modulates body ownership and the perceived body boundary (Ataria et al., 2015; Dor-Ziderman et al., 2016). These changes were associated with beta oscillations in a large cortical network, centered over right temporo-parietal cortex (Dor-Ziderman et al., 2013, 2016), a region known to be involved in self-identification and a shift from the first-person perspective (1PP) to a 3PP (Blanke et al., 2002, 2005; Ionta et al., 2011). Related more recent work also reported changes in self-location (Dambrun et al., 2023) and 1PP in meditation practice (Nave et al., 2021) and highlighted beta-band oscillatory changes in the medial parietal cortex (Trautwein et al., 2024). While these studies launched important research on specific aspects of the minimal self in meditation, they did neither experimentally manipulate nor behaviorally measure changes of the minimal self (such as changes in self-identification with the body) during the recorded meditation sessions, relying instead on in-depth verbal interviews about subjective experiences that are, however, prone to participant and experimenter biases (i.e., Adler, 1973; Rosenthal and Fode, 1963).

To experimentally manipulate the minimal self, we here developed a meditation research platform using immersive virtual reality (VR) to create a contrast between a de-centered viewpoint from a third-person (3PP) and a first-person perspective (1PP) during ongoing meditation practice. We gauged changes in the feeling of separation/detachment and the minimal self (self-identification, perceived body boundary), and measured changes in the HEP, immediately after the meditation session. We hypothesized that in the 3PP versus 1PP condition, there will be (1) stronger sensations of detachment and disconnection, (2) reduced salience of the perceived body boundary, and (3) differential self-identification with the body, (4) Based on previous findings of HEP changes reflecting changes in the minimal self (Park et al., 2016), we expected a difference in HEPs in the 3PP versus 1PP condition.

2. Materials and methods

2.1. Participants

We tested a group of 23 right-handed healthy participants (12 female, 11 male) for the study. Sample size was determined based on the effect size (0.72) for the HEP effect between synchronous and asynchronous conditions from Park et al. (2016). A paired *t*-test with an alpha level of 0.05 and a power of 0.9 was assumed for the estimation of the sample size (G*Power 3.1.9.7 software, Faul et al., 2007). Participants were all right-handed and proficient in English, aged from 19 to 48 years (mean: 28.7 years, standard deviation: 7.6 years). They were all non-meditators who reported no prior experience with meditation practice. Exclusion criteria were the presence of neurological or psychiatric disorders and substance abuse. Participants gave informed consent before the experiment, and a compensation of 20 CHF per hour was paid after completion of the experiment. The study was approved by the Swiss Ethics Committees on research involving humans (Project ID: 2021–00,358).

2.2. Virtual-reality experimental setup

The VR immersion platform developed for this study includes an in-house real-time volumetric body scanning system (Albert et al., 2019) using 4 cameras (Kinect Azure cameras, Microsoft, Washington, USA) mounted on a metallic frame, a VR headset for visual immersion (HP Reverb G2, Hewlett-Packard, USA) with 107° diagonal FOV and a resolution of 2160 × 2160 pixels per-eye), and earplugs for audio immersion (DH Gold series, Italy). The experiment was developed with our custom-made open-source software ExVR (<https://github.com/Inco-ep/ExVR>) which uses Unity3D (Unity Technologies, USA) for real-time 3D rendering.

Two audio-visual virtual environments were designed for the experiment. The virtual laboratory environment (Fig. 1A) was a 3D replica of the experimentation room; it was used for welcoming participants into VR and as an intermediate place where they answered questionnaires and performed tasks while still immersed. The virtual forest environment (Fig. 1B) represented an outdoor scene for immersing participants in a natural landscape for the meditation (i.e., trees and vegetation moving with the wind; birds chirping; sound of river flowing in the background based on custom binaural audio recordings in the mountains).

Our body scanning technology allows reconstructing a 3D representation of the body of participants located in the field of view of the cameras, either in real-time or by replaying pre-recorded 3D captures (Albert et al., 2019; Vuarnesson et al., 2024). The VR platform thereby allowed immersing participants in different virtual environments where they could see a 3D representation of their own body (collocated with their physical body) while the movements of their body were captured and shown in real-time with their actual movements (Fig. 1C, E, F; see (Vuarnesson et al., 2024) for video examples). 3D representations of other people (such as a person providing the meditation instructions) could also be integrated into the virtual environments (Fig. 1D), and this person could be physically co-present with participants during the experiment (i.e. real-time capture) or be a previously recorded person (Fig. 4).

2.3. Experimental design and procedure

The experiment followed a single-factor within-subject design to compare subjective reports, behavioral, and physiological measurements between two conditions involving a 15-minute meditation session in immersive VR. The order of the two meditation conditions (3PP, 1PP) was randomized across participants. Three short questionnaires and one behavioral task were performed inside VR immediately after both meditation conditions for evaluating differences in disembodiment, mindfulness, and perceived body boundary (see below for details). A more extensive questionnaire was administered after each meditation session, and outside of VR, to assess our participants' states of consciousness during meditation more globally. The physiological signals recorded during the whole experiment included electroencephalogram (EEG), electrocardiogram (ECG), and respiration.

The experiment took place in a dedicated room furnished to provide a relaxing atmosphere; dimmed lights, a square carpet on which participants walked without shoes, and soft cushions at the center on which they were sitting during the experiment. Once comfortably installed, participants were equipped with the VR headset and earplugs. Participants were first immersed in the virtual laboratory environment (a virtual room looking like the actual laboratory room) and habituated to the interaction modalities and to the view of their own avatar. After a few minutes of habituation, they were asked to fill the Perceived Body Boundary Questionnaire (PBBQ), which reflects the perceived salience of the body boundary and has been used before in meditation research (Dambrun, 2016; Hanley et al., 2020).

Participants then 'met' with a virtual meditation guide (a professional meditation teacher prerecorded in the same virtual room using

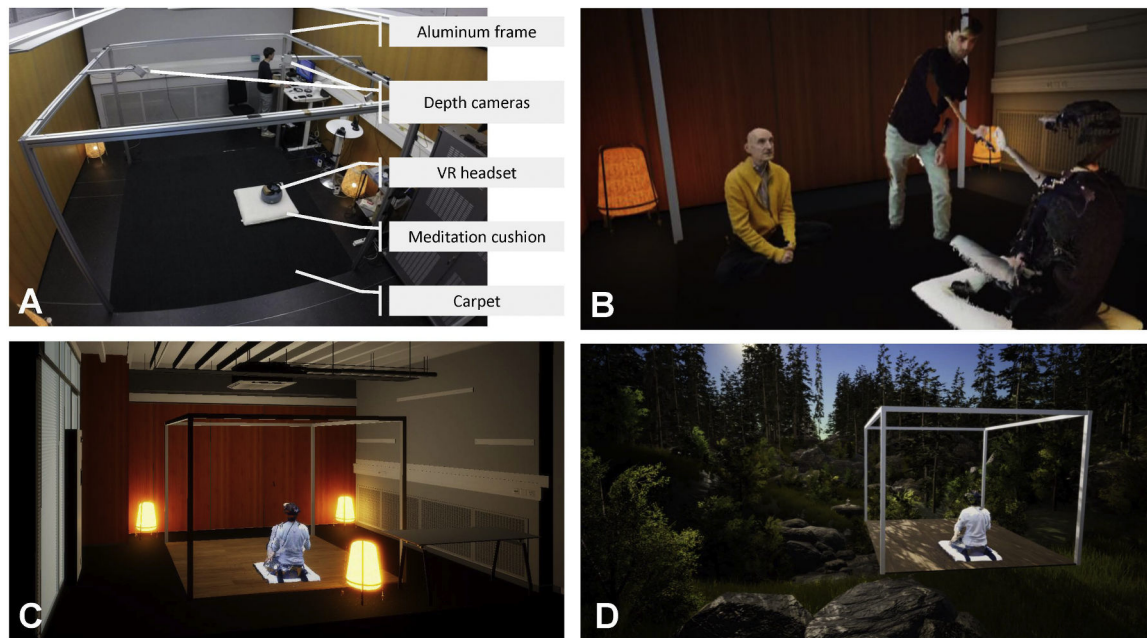


Fig. 1. Experimental setup and mixed-reality environment for the immersive meditation experiments. A) a virtual laboratory room and equipment, B) the interactions between the participant, the experimenter, and the virtual meditation guide in the virtual laboratory room, C) a meditator sitting in the virtual laboratory room D) a meditator sitting in the virtual forest for meditation.

the same VR system) inviting them to carry out the meditation session in a different VR ‘place’. The meditation guidance was recorded by a professional meditation teacher with over 30 years of personal practice (>20,000 hours) in Tibetan Buddhism and Early Buddhist traditions. He also has extensive experience as a teacher in Dharmasala, throughout India, and internationally. He has also been involved in research either

as a long-term practitioner/participant or as a co-developer of meditations in several research labs in Europe and the US. After a short transition period (2 s), participants found themselves immersed in the virtual forest environment (Fig. 2A). They were then instructed to follow the verbal guidance, provided by the prerecorded virtual meditation guide. After an invitation to visually explore the virtual forest

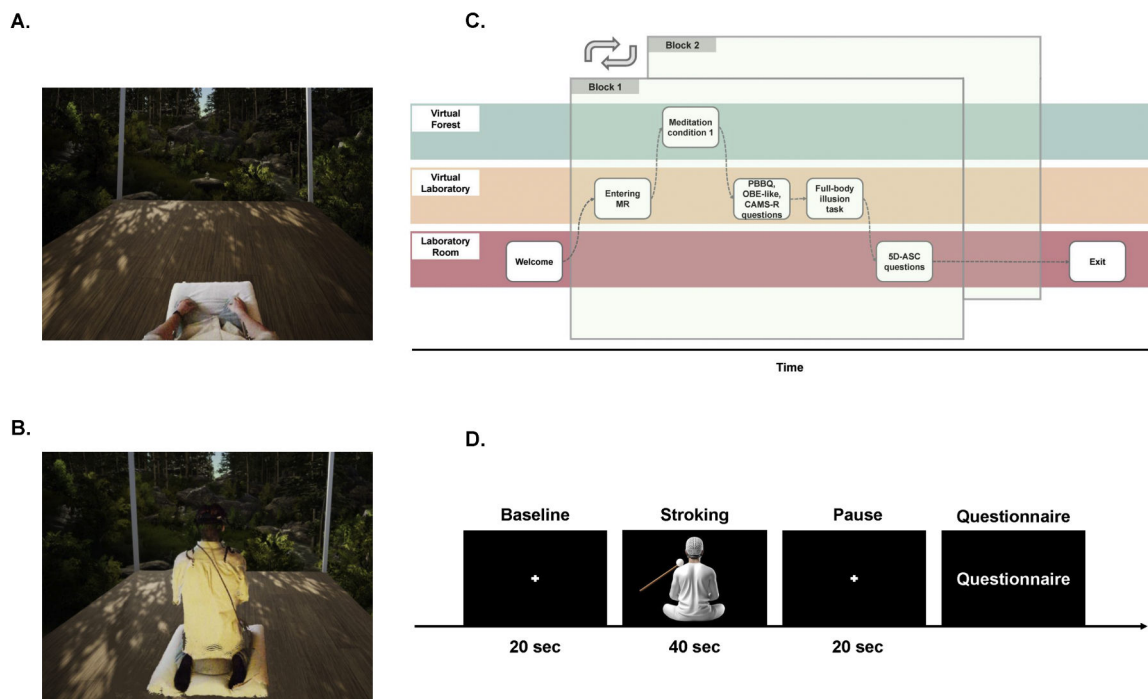


Fig. 2. A) Participants see their bodies in first-person view when immersed in the virtual forest environment. B) In the 3PP condition, the visual perspective is manipulated to show the participant’s body in a third-person view. C) A simplified experiment flow of one typical block in the study. The experiment consists of two blocks, one per condition (3PP or 1PP). In each bloc, the meditation sessions were followed by subjective evaluations with questionnaires in MR (PBBQ, OBE, and CAMS-R), a behavioral task in MR (full body illusion), and a last questionnaire outside MR (5D-ASC). The order of the two meditations was counterbalanced across participants. D) Illustration of one block of the FBI task.

environment, they were asked to close their eyes and were then guided through a mindfulness exercise designed to help them calm their mind and focus their awareness on their body. The meditation design was based on components of traditional meditation, including focused bodily awareness and open monitoring, which have been widely used in meditation research. The meditation guidance was discussed in close collaboration with the expert meditator and meditation teacher to ensure that the meditation protocol facilitates a seamless transition through the meditation experience. This design carefully emphasizes perspective shifts while minimizing variations in verbal guidance across conditions (1PP vs 3PP), maintaining clarity and consistency throughout the practice. The 3PP condition consisted of focused awareness on different parts of the participant's body (Dahl et al., 2020; Lutz et al., 2008; Gan, Zhang, and Chen, 2022; Miram et al., 2013), with particular emphasis on the torso (5 min). After this, participants were guided through an open monitoring meditation (i.e., Hölzel et al., 2011; Kessel et al., 2016; Lutz et al., 2008) during which they were instructed to take a de-centered and distanced perspective and witness moment-to-moment fluctuations occurring in their conscious experience. Up to this point, participants had always experienced the virtual forest and their bodies from their habitual embodied viewpoint. Now this viewpoint was slowly and progressively shifted to a third-person perspective, by placing their virtual viewpoint to a slightly elevated and posterior position behind their virtual body (Fig. 2B). After an instruction to witness their body from this 3PP, the guidance continued with open monitoring. The 1PP condition had the same length but differed in two main aspects from the 3PP condition. Following the focused awareness on different body parts, (1) participants followed meditation guidance that centered on external objects in the forest (i.e., attention was focused on objects in the virtual forest such as trees and rocks, and not on body and self as in the 3PP meditation condition). In addition, (2) there was no shift in viewpoint during meditation and participants remained in 1PP. We controlled visually for the visual displacement (of the viewpoint during 3PP) by moving during 1PP the entire shelter area within the virtual forest and by displacing it by the same amplitude/distance and with the same speed as the 3PP condition (but now participants remained in 1PP) (see Fig. 2).

After each meditation condition, participants first returned to the virtual laboratory where they were asked to answer several questions while still immersed in VR. The PBBQ was asked again so as to compare its score with the baseline measured before meditation. This was followed by the Cognitive and Affective Mindfulness Scale (CAMS-R), to capture mindfulness states that reflects well-being and emotion regulation as a dynamic state (Feldman et al., 2007; G. 2022), and by an Out-of-Body Experience sensation questionnaire (OBE), developed in-house to evaluate subjective aspects of out-of-body experiences (Song, 2020; Wu et al., 2023). For statistical analysis of the questionnaire responses, we used a Linear Mixed Effect (LME) model (significance level $p < 0.05$, two-tailed) and Bayes Factor (implemented by the BayesFactor package, Morey et al., 2011) to compare the difference between 3PP condition and 1PP condition.

Next, a full-body illusion task was then administered to evaluate potential differences in sensitivity to multisensory visuo-tactile stimulation between the 3PP and 1PP conditions. During the full-body illusion task, participants see a representation of their body as seen from a position behind their body while their back is stroked by the experimenter (Aspell et al., 2009; Bayer et al., 2023; Lenggenhager et al., 2007, 2009; Park et al., 2016). The present full-body illusion was adapted to the sitting position of the participants in the VR environment, and the stroking was applied with a stick ending with a white ball held by the experimenter (unaware of the condition). We tested the full-body illusion in two conditions, in a synchronous visuo-tactile stimulation (i.e. participants saw the ball touching their back synchronously with the moment when they felt the touch on their back) and in an asynchronous condition (i.e. participants saw the ball touching their back with a 500 ms delay to the moment when they felt the touch on their back). The

synchronous and asynchronous conditions were each repeated twice in randomized order. All four full-body illusion trials started by displaying a fixation cross in front of participants for 20 s, followed by 40 s of visuo-tactile stimulation (see Fig. 2D). At the end of each trial (as in Aspell et al., 2009; Park et al., 2016), we gauged participants' mislocation of touch ("I felt as if the touch was located where I saw the stroking"), self-identification ("I felt as if the body I saw was my body"), and a control question ("I felt as if I had more than three bodies"), using a 7-point Likert scale.

Finally, participants took off the VR headset and earplugs and were given a tablet on which to fill out the 5-Dimensional Altered States of Consciousness Rating Scale questionnaire (5D-ASC, Schmidt and Berkemeyer, 2018). After a short break, the other condition was performed following a similar procedure.

2.4. EEG recording

For the entire duration of the experiment, EEG was recorded using a 64-channel eegoTM mylab system (ANT Neuro). Based on the five percent electrode placement system (Oostenveld and Praamstra, 2001), a total of 65 EEG channels were placed. These included two mastoid electrodes placed behind the ears (M1 and M2), the CPz electrode selected by the system as the online reference of all channels, and the AFz electrode used as the ground electrode. The impedance of all EEG channels was kept below 20 k Ω for the whole experiment. The Lab Recorder was used for online recordings of the Lab Streaming Layer (LSL, <https://github.com/scn/labstreaminglayer>) at a sampling rate of 512 Hz.

2.5. ECG and respiration recordings

ECG and breathing signals were simultaneously recorded through bipolar channels connecting to the EEG system. ECG signals were collected with two bipolar ECG channels diagonally placed, one attached between the lower two ribs on the left side of the body, and the other under the right collarbone, around 5 cm from the sternum. Breathing was recorded with a respiration belt (Spec Medica) attached to the lower chest (thoracic diaphragm region) of the participants.

2.6. Analysis of the heartbeat evoked potentials

All analyses of ECG, EEG, and respiration signals were done in MATLAB (The MathWorks, Inc.). EEG signals were analyzed using EEGLAB (Delorme and Makeig, 2004) and fieldtrip (Oostenveld et al., 2011).

ECG pre-processing. The ECG signal was first filtered with high-pass and low-pass frequency (0.1 – 40 Hz). To detect the R-peak of heartbeats, the filtered ECG signals were decomposed into 5 scales based on the maximal overlap discrete wavelet transform (Biran and Jeremic, 2023). The ECG waveforms were reconstructed with wavelet coefficients of only the fourth and fifth scale which corresponded to 11.25–22.5 Hz and 5.625–11.25 Hz. The R-peak detection was applied to find the peak time of the squared values of the reconstructed signals. The peak detection results were visually inspected throughout the experiment for all participants. A threshold of 10,000 microvolts in ECG amplitude lasting for >200 s was set for all participants to exclude artifacts caused by motion or pull of ECG cables during the experiment. Detected noisy periods were excluded from further analysis.

EEG pre-processing. Bad channels were marked due to an unstable EEG signal during the setup of the EEG cap, only one channel for one participant was removed and was interpolated with the average amplitudes of surrounding channels. Continuous EEG was filtered with the same bandpass filter as for ECG (0.1 – 40 Hz), followed by segmenting the continuous EEG into epochs from 100 ms before to 800 ms after the R-peak. EEG epochs were baseline-corrected with the pre-stimulus time [–100, 0] ms, as widely used for HEPs studies (Coll et al., 2021; Kumral

et al., 2022; Terhaar et al., 2012). Trials with absolute values in their amplitudes higher than 100 microvolts were automatically detected and removed for further analysis. This resulted in an average of 787 (SD: 156) trials during the 3PP condition and an average of 730 (SD: 146) trials for the 1PP condition. The remaining EEG trials were then re-referenced to the average of the mastoid channels, as in previous HEPs studies (Coll et al., 2021). Importantly, the mastoid channels were chosen as the re-reference (instead of the common average), in order to diminish the impact of alpha-band oscillations in the posterior sites (which was observed in our data such as electrodes O1, PO7, etc.), as has been supported by numerous meditation studies (Katyal and Goldin, 2021; Lee et al., 2018; Lomas et al., 2015). The EEG trials were then fitted into an independent component analysis (ICA) and the waveform and topography of all components were visually inspected. The components related to eye blinks and saccades were removed. An average of 1.48 (SD: 0.73) independent components were removed in the ICA. The clean EEG trials were then averaged separately for both 1PP and 3PP conditions for each participant.

HEPs statistical analysis. To test whether and when the HEPs showed a difference between the two conditions, a point-to-point paired-*t*-test (significance level: 0.05) was applied to the HEPs across time with the LIMO toolbox (Pernet et al., 2011). This way, the time windows that showed a significant difference between both meditation sessions were detected in the time range from 0–800 ms. HEP amplitudes during these detected time windows at the Fz channel were then averaged for paired-*t*-tests (significance level 0.05, two-tailed) that compared the within-subject effect of meditation sessions. To test the topographic difference of HEPs between conditions in the detected time windows, a nonparametric randomization test using the Monte-Carlo method (10,000 randomizations) was applied to estimate the significance probabilities for each channel without multiple corrections.

2.7. Control analysis of physiological recordings

To further exclude the possibility that the HEPs effect was caused by EEG artefacts related to heartbeats and breathing, a set of control analyses was completed including ECG analysis (average ECG amplitude in the HEPs time window, heart rate and heart rate variability) and respiratory analysis (respiration rate and respiration rate variability).

Surrogate heartbeats. To demonstrate that the HEP effects were synchronized with the heartbeats rather than resulting from random fluctuations of the amplitude, we generated 500 permutations of heartbeats separately for each condition following the previous studies (Babo-Rebelo et al., 2016; Park et al., 2016). To keep the same inter-beat interval and variability as the original R-peaks, the R-peaks were shuffled within each condition between trials, each trial lasting 20 s segmented from the 15-minute-long meditation session. The timing of the heartbeats in trial *i* was randomly assigned to trial *j*. After the permutations, the other analytical steps including the threshold of rejecting noisy trials remained the same as the aforementioned HEP analysis. Time windows that showed significance between two conditions were detected with the point-to-point paired-*t*-test (significance level: 0.05). The continuous time points that showed significance in the comparison between the 1PP and the 3PP condition were considered potential clusters. For each permutation, we extracted the largest positive sum of *t* values among the clusters, and compared the distribution of those surrogate values with the original sum of *t* values.

ECG analysis. After the R-peak detection described in the section on ECG pre-processing, the ECG signals were segmented into epochs of the same length for the HEPs analysis, i.e. [−100 800] ms. These epochs were averaged separately for 1PP and 3PP conditions, followed by the statistical test of average ECG amplitudes in the time window that showed the HEPs difference. Besides, the inter-beat intervals (IBI) were calculated as the time interval between two R-peaks. Time intervals smaller than 1500 ms or bigger than 500 ms (i.e. heartbeats at <40 or >120 bpm) were excluded. The number of heartbeats per minute during

both meditation sessions was calculated as $60/(0.001 \cdot \text{IBI})$. Additionally, to quantify the heart rate variability (HRV) (Shaffer and Ginsberg, 2017), the root mean square of successive heartbeats (RMSSD) was evaluated for each meditation condition.

Respiration analysis. The respiratory signals were first filtered with a high-pass filter of 0.2 Hz and a low-pass filter of 0.8 Hz, as usually done to exclude signals outside of normal respiration rates (12 ~ 20 breaths per minute, Nicolò et al., 2020; Xu et al., 2021). Breathing peaks were detected by identifying the local maximum amplitudes of respiratory signals using the *BreathMetric* package (Noto et al., 2018). Similar to the ECG signals, the respiratory signals higher than a threshold of 10,000 microvolts lasting longer than 200 s were excluded for further analysis. The breath rate variability was also measured with the root mean square of successive differences (RMSSD) (Kumar et al., 2020; Soni and Muniyandi, 2019).

2.8. Source estimation

To identify the brain areas where the HEP amplitudes differed across meditation conditions, the BrainStorm toolbox was used for the source estimation (Tadel et al., 2011) during the time window specified in the HEPs statistical analysis section. The head model was computed with OpenMEEG BEM based on the cortical surface of Colin27 MNI template, utilizing adaptive integration to enhance the precision (Gramfort et al., 2010). The sources of the HEP were determined using a weighted minimum-norm current estimate with the dSPM option where the dipole orientations were unconstrained for each meditation condition and each subject. Parameters included depth weighting with an order of 0.5 and a maximal amount of 10, a signal-to-noise ratio of 3, and a diagonal noise covariance. HEP differences were tested using a paired *t*-test with an alpha level of 0.01 without correction for multiple comparisons.

2.9. Statistics

For measures including the OBE-like sensations, 5D-ASC questions, PBBQ, and physiological measures, LME models were also applied to examine the effect of experimental conditions (1PP against 3PP). For the full-body illusion, we applied a Linear Mixed Effect (LME) model to examine the 2-by-2 design (experimental condition * visuo-tactile synchrony). The maximal LME model explored the fixed effects for meditation sessions, synchrony, and the interaction between them, plus the random intercepts and order slopes by subject number. This structure reflects our hypothesis that trial order effects vary across individuals while avoiding arbitrary removal of terms that could mask meaningful variation (Barr et al., 2013). Model reduction was not performed to prevent over-optimization of this dataset. For all the abovementioned models, the participant number and the order of meditation sessions were set as random effects. To link the different measures including the full-body illusion, the PBB and the HEP, correlation analysis was conducted for the 3PP-1PP effects while multiple comparisons were corrected with the Bonferroni approach.

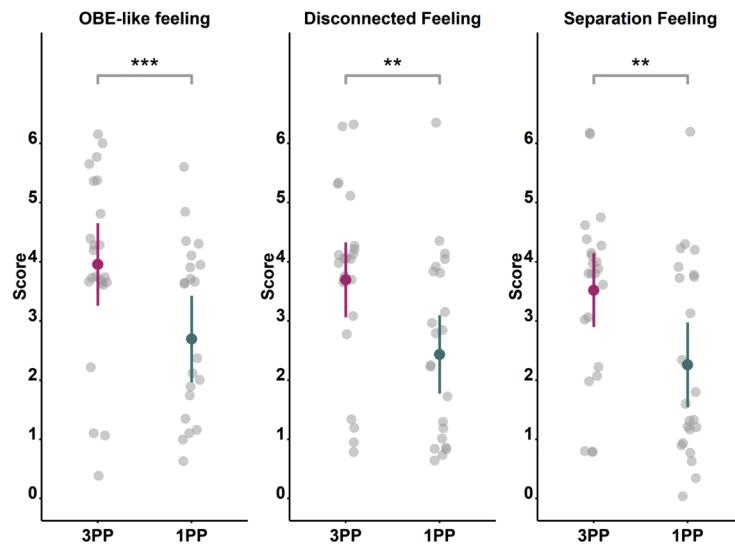
3. Results

3.1. Stronger OBE-like sensations in the 3PP condition

Results of the OBE questionnaire (Wu et al., 2023) showed that participants experienced stronger OBE-like sensations in 3PP versus 1PP condition (Fig. 3), as indexed by higher subjective ratings on the items of disconnection ($\chi^2(1) = 10.20, p = 0.0014, BF_{10} = 8.91$), feeling of separation ($\chi^2(1) = 9.51, p = 0.002, BF_{10} = 7.19$), and OBE-like feeling ($\chi^2(1) = 11.30, p = 0.00078, BF_{10} = 12.38$). No other item of the OBE questionnaire showed significant differences between the two conditions (all $p > 0.05$).

Concerning the 5D-ASC, the dimension of disembodiment showed a

A. Disembodiment in OBE-like questionnaire



B. Disembodiment in 5D-ASC

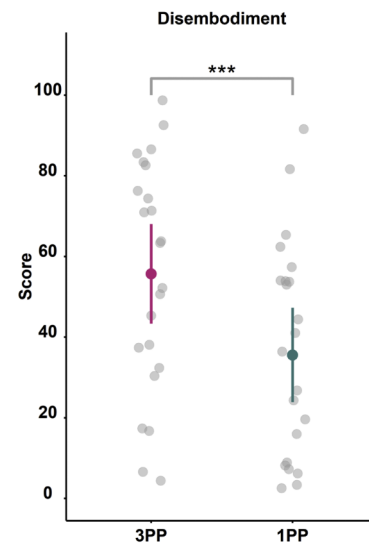


Fig. 3. OBE-like sensations are stronger in the 3PP (pink) versus 1PP (green) condition. Data are shown for OBE-like feeling (A, left), disconnection (A, middle), separation (A, right) (range: 0–10) of the OBE-questionnaire (Wu et al., 2023) and the disembodiment item of the 5D-ASC questionnaire (Figure B, in percentage; range: 0–100).

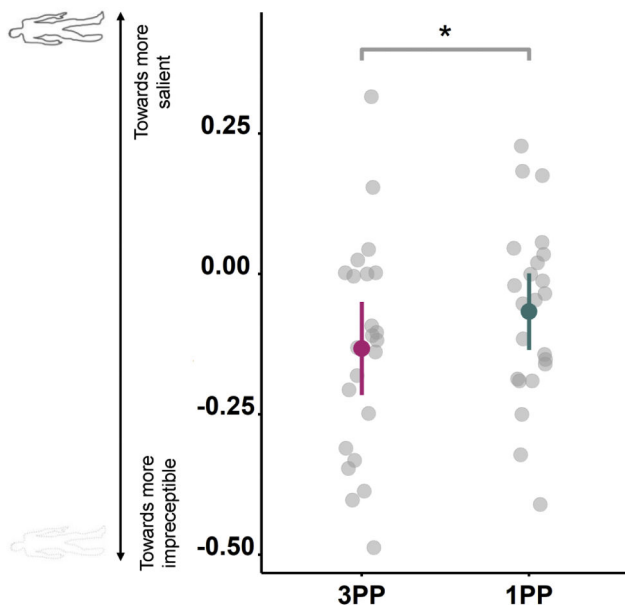


Fig. 4. Difference scores of the perceived body boundary after both meditation sessions compared to the baseline (zero score represents a score equal to baseline; a negative value a more blurred body boundary). Data show a greater reduction of the perceived body boundary in the 3PP condition (pink) compared to the 1PP condition (green).

significant difference (Fig. 3B) between the 3PP condition ($M = 55.70$, $SD = 28.57$) and the 1PP condition ($M = 35.58$, $SD = 27.05$): $\chi^2(1) = 11.33$, $p = 0.00076$, $BF_{10} = 12.55$). The other ten dimensions did not show any difference across conditions (all $p > 0.05$; see Table 1).

3.2. Reduction of perceived body boundary in the 3PP condition

Changes in perceived body boundary were computed separately for each meditation condition as the difference of the PBBQ score measured before (baseline) and after each meditation condition. Both conditions

showed a significant or marginal significant reduction in PBBQ (PBBQ score after meditations was lower than baseline, 3PP condition: $M = -0.13$, $SD = 0.19$, $t(22) = -3.32$, $p = 0.003$, $BF_{10} = 12.13$; 1PP condition: $M = -0.07$, $SD = 0.16$, $t(22) = -2.04$, $p = 0.054$, $BF_{10} = 1.25$). The reduction in the 3PP condition was significantly higher than in the 1PP condition ($\chi^2(1) = 6.46$, $p = 0.011$). Bayes Factor however indicated that this result was inconclusive ($BF_{10} = 2.65$).

3.3. Reduced self-identification in the 3PP condition correlates with changes in perceived body boundary

In line with previous findings (Moon et al., 2024; Nakul et al., 2020; Lenggenhager et al., 2007), we replicated the main effect of stroking synchrony ($\chi^2(1) = 33.04$, $p = 9.05 * 10^{-9}$) on self-identification. Moreover, the 3PP condition significantly reduced self-identification compared to the 1PP condition (main effect of experimental condition: $\chi^2(1) = 11.68$, $p = 6.32 * 10^{-4}$) and there was also an interaction between experimental condition and visuo-tactile stroking condition ($\chi^2(1) = 4.08$, $p = 0.043$). Post-hoc testing indicated significantly lower self-identification during the 3PP vs. 1PP condition during asynchronous stroking (3PP condition: $M = 4.52$, $SD = 1.79$; 1PP condition: $M = 5.28$, $SD = 1.64$; $t(45) = 3.24$, $p = 0.0023$, $BF_{10} = 14.11$), which was absent during synchronous stroking (3PP condition: $M = 5.61$, $SD = 1.56$; 1PP condition: $M = 5.80$, $SD = 1.29$; $t(45) = 1.39$, $p = 0.17$, $BF_{10} = 0.39$). Thus, self-identification with the seen avatar was weaker in the 3PP condition and this was particularly the case during asynchronous stroking.

Concerning mislocalization of touch there was a main effect of synchrony ($\chi^2(1) = 203.78$, $p = 2.0 * 10^{-16}$) with significantly larger ratings in the synchronous vs. asynchronous visuo-tactile condition, as reported previously (i.e., Lenggenhager, Tadi, et al., 2007). There was no main effect of intervention ($\chi^2(1) = 0.57$, $p = 0.45$) nor interaction effect ($\chi^2(1) = 1.68$, $p = 0.19$). For the control question, there were no main effects (visuo-tactile synchrony: $\chi^2(1) = 3.41$, $p = 0.065$; experimental condition: $\chi^2(1) = 7.7 * 10^{-3}$, $p = 0.93$) and no interaction ($\chi^2(1) = 0.63$, $p = 0.43$).

Additionally, we explored whether the changes in self-identification (during the full-body illusion task) correlated with the PBBQ scores. For

Table 1

The subjective reported altered state of consciousness in percentage (%) according to the 5D-ASC (the dimension that showed significance ($p < 0.05$) had been marked in bold font).

No	Dimensions	3PP condition M (SD)	1PP condition M (SD)	LME			BF10
				df	χ^2	p	
1	Experience Of Unity	40.72 (25.49)	37.68 (22.01)	22	1.17	0.28	0.36
2	Spiritual Experience	29.55 (23.65)	25.01 (16.83)	22	2.48	0.12	0.61
3	Blissful State	43.10 (30.08)	37.39 (24.74)	22	3.56	0.059	0.93
4	Insightfulness	38.22 (24.15)	34.41 (22.67)	22	1.51	0.22	0.42
5	Disembodiment	55.70 (28.57)	35.58 (27.05)	22	11.33	0.00076	12.55
6	Anxiety	19.86 (16.17)	15.18 (14.31)	22	1.97	0.16	0.50
7	Complex Imagery	31.81 (25.10)	28.06 (25.95)	22	1.31	0.25	0.38
8	Elementary Imagery	21.70 (23.96)	17.49 (17.90)	22	1.04	0.31	0.34
9	Audio-Visual Synthesiae	30.19 (24.39)	34.57 (25.38)	22	1.57	0.21	0.43
10	Changed Meanings of Percepts	37.52 (27.17)	35.59 (22.59)	22	0.27	0.60	0.25

this, we compared the difference in self-identification with the PBBQ scores between conditions. Correlation analysis revealed a positive correlation between the PBBQ difference between conditions and self-identification for synchronous stroking condition of the full-body illusion ($r = 0.52$, $p = 0.01$, see Fig. 5). Thus, the stronger participants identified with the seen body (self-identification), the stronger they reported a transparent body boundary in the 3PP versus 1PP condition. This correlation was absent for asynchronous stroking ($r = -0.15$, $p = 0.48$).

3.4. Stronger, more negative, HEPs in the 3PP condition

First, EEG analysis revealed a prominent HEP at electrode Fz (Fig. 6A), similar to previous HEP work (Fukushima et al., 2011; Park et al., 2016; Tanaka et al., 2023). Second, the averaged HEP waveform at electrode Fz in the 3PP condition was characterized by a significantly more negative amplitude in a time window ranging from 313 to 754 ms (timepoint-by-timepoint t -test from 0–800 ms after the heart beat; $p < 0.05$) (Fig. 6A). Third, full-scalp analysis during this time window revealed two frontal electrodes (Fz, FCz) differing significantly between both conditions ($p < 0.01$) (permutation t -test; Monte-Carlo). The average amplitudes at both electrodes for this time period were further tested with a paired- t -test, showing a more negative HEP amplitude in the 3PP condition (Fz: $M = -0.21$, $SD = 1.70$; FCz: $M = -0.21$, $SD = 1.70$) compared to the 1PP condition (Fz: $M = 0.56$, $SD = 1.58$; FCz: $M = 0.56$, $SD = 1.58$) at electrode Fz ($\chi^2(1) = 13.28$, $p = 0.00027$, $BF_{10} = 21.89$) and FCz ($\chi^2(1) = 9.41$, $p = 0.0022$, $BF_{10} = 21.88$).

Additionally, we explored whether changes in self-identification during the full-body illusion were associated with changes in HEP amplitude during meditation. Specifically, we compared the differences in self-identification with the HEP amplitude differences between conditions (average amplitude of Fz and FCz electrode). Correlation analysis indicated a significant positive relationship between the HEP difference and self-identification in the synchronous stroking condition ($r = 0.57$, $p = 0.03$; see Fig. 6D). This finding suggests that a stronger identification with the seen body (self-identification) corresponds to enhanced neural responses in the 3PP versus 1PP condition. In contrast, no significant correlation was observed for the asynchronous stroking condition ($r = 0.2$, $p = 1$) after correcting for multiple comparisons with Bonferroni in which the p values were multiplied by the number of comparisons (Curtin and Schulz, 1998).

Finally, to identify the brain regions reflecting the significant condition differences in HEP amplitude at frontocentral scalp electrodes (Fig. 6B), we reconstructed the sources of HEP during the time window from 313 to 754 ms separately for the 3PP condition and 1PP condition. This analysis localized HEP differences in the posterior cingulate cortex (paired t -test; $p < 0.01$) (PCC, see Fig. 6E) and the medial prefrontal cortex (mPFC).

3.5. HEP control analysis

Surrogate R-peaks results. The summed t values of the clusters were computed for the 500 permutations and the largest cluster was picked by selecting the cluster with the largest summed t value at each permutation. None of the 500 permutations showed a summed t value as large as the original ones obtained from the HEP time-locked to real R-peaks (Fig. 7A), confirming that the differential HEP effect is locked to the heartbeat and not due to random fluctuations of the HEP amplitude.

ECG results. Further analysis revealed that these HEP changes cannot be accounted for by differences in ECG parameters. Control

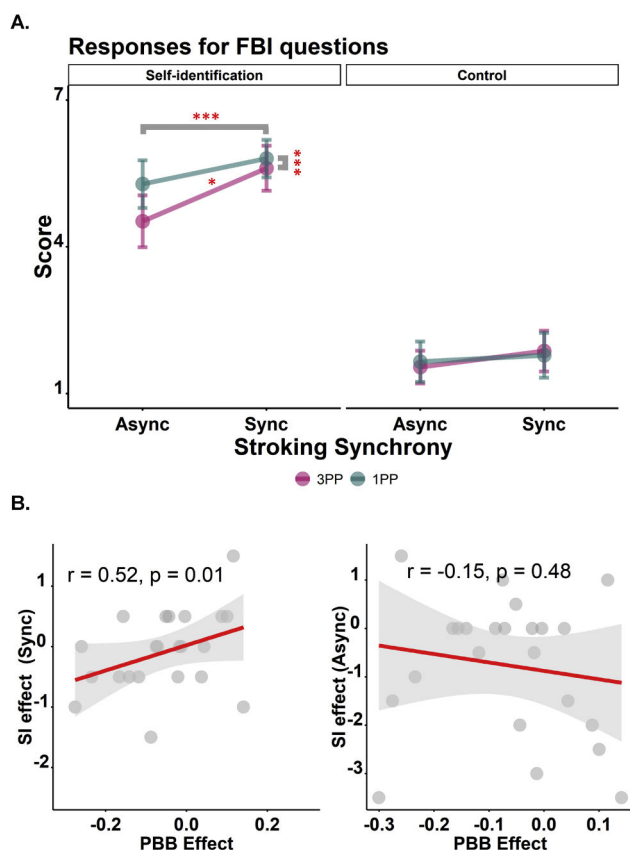


Fig. 5. A. Results for self-identification (left) and a control question (right) are shown for synchronous and asynchronous stroking for the 3PP (pink) and 1PP condition (green). Dots represent the average scores and the error bars are the 95 % confidence interval. The significance of main effects and interaction is indicated (* represents $p < 0.05$, **** represents $p < 0.001$). B. Difference in self-identification ratings (3PP - 1PP) correlates with the difference in perceived body boundary (PBBQ difference between conditions). This was found in the synchronous stroking condition (left), but not for the asynchronous stroking condition.

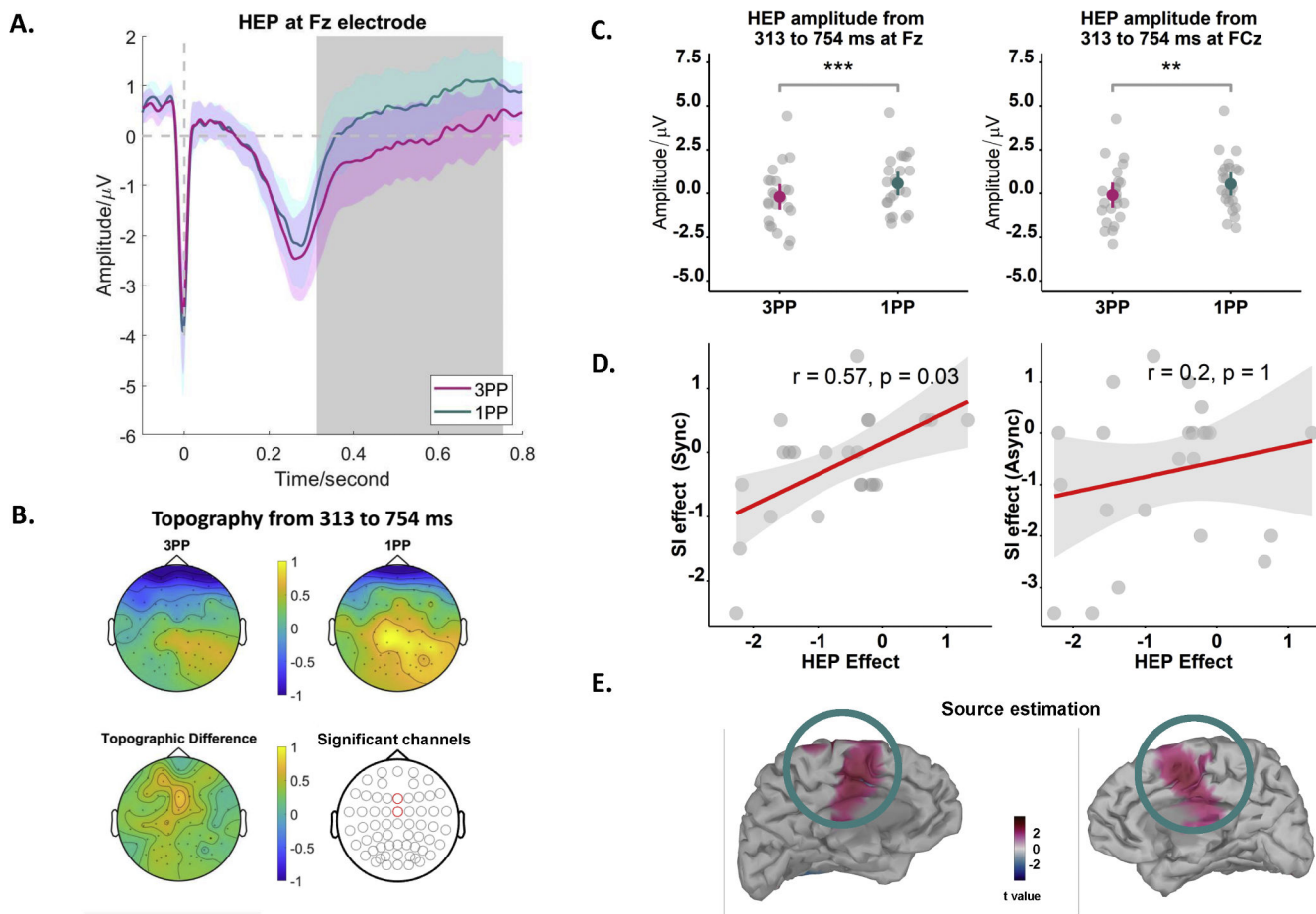


Fig. 6. A. HEPs are significantly lower amplitude in the time window of 313 – 754 ms (marked grey) in the 3PP vs. 1PP condition. The pink and green shadowed areas represent the 95 % confidence interval separately for 3PP and 1PP condition. B. Topography of HEP in the 3PP condition (left), the 1PP condition (middle), and for the difference between both conditions (right). C. Boxplot of HEP amplitude at Fz electrode for both conditions. Significant difference was found only in two frontal sites (Fz, FCz). (D) The difference in self-identification ratings (3PP - 1PP) correlates with the difference in HEP amplitude (HEP difference between conditions). This correlation was found in the synchronous stroking condition (left), but not for the asynchronous stroking condition. (E) Source estimation for the HEP from 313 to 754 ms.

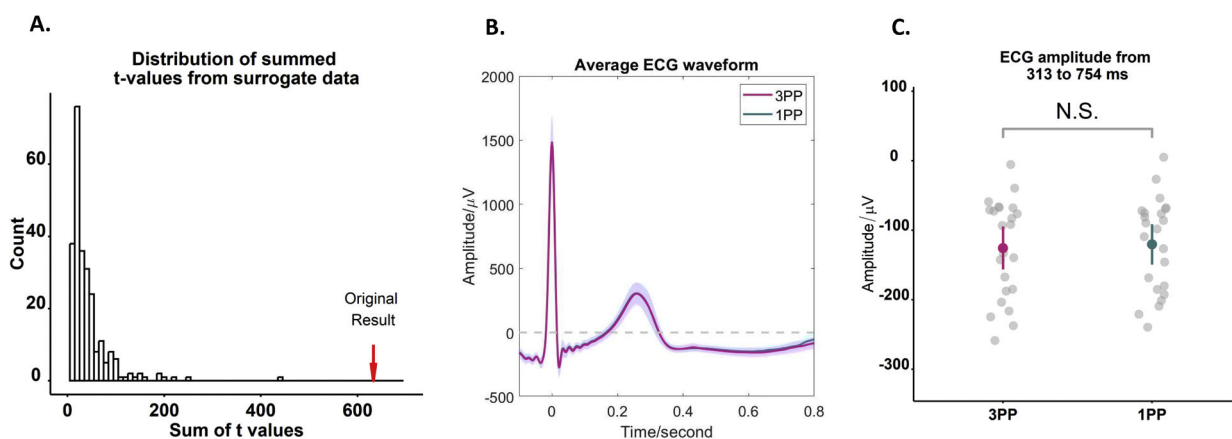


Fig. 7. A) The histogram of the distribution of the maximal summed t values, derived from 100 permutations of surrogate heartbeats. Notably, the original summed t value (indicated by the arrow) lies outside the distribution of statistics generated from surrogate data. B) The average ECG waveforms in the HEPs time window (–100 to 800 ms) during the 3PP and 1PP conditions. C) Mean and confidence interval of the ECG amplitudes in the specified time window (313 to 754 ms).

analysis, conducted to examine potential cardiac confounds (ECG waveforms were obtained by averaging the ECG amplitudes, Fig. 7B), showed no differences between the 3PP and the 1PP condition in the ECG amplitude in the same time window that showed a HEP difference,

i.e., ranging from 313 to 754 ms (Fig. 7C, see Table 2 for the detailed descriptive and statistical tests).

Beyond the ECG amplitudes, we measured heart rate and heart rate variability during two sessions to exclude the confound of cardiac

Table 2
Descriptive and statistical results of the control analysis of the HEP, including ECG and respiratory signals.

Measurement	Index	3PP condition M (SD)	1PP condition M (SD)	df	LME χ^2	p	BF10
ECG	ECG amplitudes	-125.57 (71.57)	-120.37 (67,27)	1	2.09	0.15	0.52
	Inter-beat interval (ms)	919.90 (128.75)	925.02 (154.23)	1	0.15	0.70	0.23
	Heart beat per minute	66.42 (9.02)	66.45 (10.08)	1	0.001	0.98	0.22
	Heart beat variability	59.08 (27.18)	56.04 (27.79)	1	0.54	0.46	0.28
Respiration	Inter-breath-interval (ms)	4824.51 (1548.65)	4937.43 (1340.45)	1	0.42	0.52	0.53
	Breathing rate per minute	13.50 (3.61)	13.02 (3.46)	1	1.45	0.23	0.40
	Breath rate variability	2655.83 (2432.49)	2813.21 (1893.81)	1	0.24	0.62	0.24

changes. Both the inter-beat interval and the heart rate did not show a difference between meditation sessions. The heart rate variability was examined with the root mean square of successive R-R interval (RMSSD). Results showed that the 3PP condition showed no difference with the 1PP condition on the heart rate variability (see Table 2).

Respiratory results. The breathing signals were extracted for the 3PP condition and 1PP condition separately. The breathing rate per minute did not show a difference between the 3PP and the 1PP condition. The pattern remained the same when calculating the inter-breath-interval. Also, the breath rate variability was compared against meditation sessions and no effect had been found, by means of RMSSD.

4. Discussion

Extending previous research on the minimal self in meditation practice (Canby et al., 2024; Dor-Ziderman et al., 2016; Droit-Volet and Dambrun, 2019; Lindahl and Britton, 2019), we here leveraged a new VR platform to perform guided meditation while experimentally manipulating the minimal self (3PP versus 1PP) and obtaining behavioral minimal self measures (changes in self-identification) and EEG measures. We report that the 3PP versus 1PP condition was associated with immediate behavioral and neural effects including (1) with stronger feelings of separation, detachment, and OBE-like sensations (5D-ASC, OBE questionnaire) and weaker self-identification with the seen body (full-body-illusion). The 3PP condition also (2) led to a more transparent body boundary (PBBQ), as reported previously for meditation practice and the magnitude of PBBQ changes between conditions positively correlated with the self-identification changes in the full-body-illusion-inducing synchronous condition. (3) HEP data revealed differential neural responses between both conditions, characterized by a more negative HEP amplitude in the 3PP condition (Park et al., 2016, 2018), linked to activation in PCC and mPFC, two structures that have previously been linked to HEPs and the minimal self. (4) Control analyses show that these changes were not caused by physiological changes including heart rate, heart beat variability, breath rate, and breath rate variability.

4.1. VR-supported meditation practice induces stronger disembodiment and reduced salience of the perceived body boundary

To manipulate the minimal self during meditation, we combined meditation practice with a VR platform that immersed participants in a virtual environment where they could view a 3D representation of their own bodies. The platform enabled us to employ different immersive perspectives in each condition. In the 3PP condition, we combined a visual transition from a first-person to third-person viewpoint with open monitoring meditation during which participants were instructed to take a de-centered and distanced perspective and witness moment-to-moment fluctuations of conscious experience. In the 1PP condition, participants were exposed to a transition of the shelter area within the

virtual forest (same speed-distance as 3PP transition), while remaining in a first-person viewpoint and instructed to engage in focusing on the environment (forest). Data show that 3PP versus 1PP condition was associated with stronger feelings of separation/detachment of our participants' self from their body and with other OBE-like sensations (OBE questionnaire; Wu et al., 2024; disembodiment items from 5D-ASC). Thus, integrating a 1PP to 3PP shift in perspective into meditation was associated with OBE-like sensations during meditation practice, comparable to such sensations reported in different experimental setups manipulating visuo-tactile in healthy individuals (Ehrsson, 2007; Ionta et al., 2011; Pfeiffer et al., 2013, 2016) or visuo-vestibular signals (Wu et al., 2024). They also correspond to disembodiment scores in the 5D-ASC (Schmidt and Berkemeyer, 2018), though less intense than reported after intake of psychedelic substances (i.e., lysergic acid diethylamide; Kraehenmann et al., 2017). The present OBE-sensations were also weaker than those reported in OBEs of neurological patients (Blanke et al., 2002, 2004, 2005; Hiromitsu et al., 2020) or spontaneous OBEs in healthy participants (Braithwaite et al., 2011; Milne et al., 2019). Additionally, further research is needed to determine how long these sensations can persist.

Moreover, the 3PP versus 1PP condition was accompanied by a less salient body boundary (PBBQ), as reported previously for meditation practices such as body scan meditation (Dambrun, 2016; Dambrun et al., 2019) or mindfulness training (Ataria et al., 2015), in novices (Hanley et al., 2020) and experts (Linares Gutiérrez et al., 2022). These data show that the 3PP condition induced a decreased, more transparent body boundary that has been argued to be of relevance for the minimal self in meditation practices (Ataria et al., 2015; Dambrun, 2016; Lindström et al., 2023; Nave et al., 2021, 2021; Trautwein et al., 2024) or intake of psychedelic substances (Canby et al., 2024). A large body of meditation research suggests that maintaining a distanced perspective on one's experiences is a crucial aspect of de-centering (i.e., Bennett et al., 2021; Kessel et al., 2016). A novel aspect of the present VR-enabled 3PP condition is that such distancing during open monitoring can be additionally supported by 'visual distancing' of the practitioner's viewpoint, potentially enhancing the ability to de-center and to re-perceive events in conscious experience, a metacognitive ability commonly cultivated by mindfulness meditators (Dahl et al., 2015; Gecht et al., 2014; Hölzel et al., 2011; Kessel et al., 2016). There is a wide variate of mindfulness practices (Dunne, 2011) and these likely tap into different behavioral and neural mechanisms (Lutz et al., 2015). Our VR-based approach may help in investigating differences between such contemplative traditions and study common and shared mechanisms of mental and visual distancing in meditation practice as well as their potential to jointly support de-centering in meditation practice.

4.2. Behavioral changes of the minimal self in the full-body illusion

We also observed condition-related changes in the full-body illusion. Following both meditation conditions, our participants were sensitive to

visuo-tactile stimulation, showing similar effects as observed previously (higher mislocation of touch; higher self-identification in synchronous- vs. asynchronous condition) (Aspell et al., 2009; Bayer et al., 2023; Lenggenhager et al., 2007; Noel et al., 2015; Park et al., 2016). Critically, self-identification was differently modulated by our meditation conditions and characterized by lower self-identification in 3PP vs. 1PP condition. Moreover, this differential decrease across conditions was driven by lower values during the asynchronous 3PP condition that were equally strong between 3PP and 1PP during synchronous stimulation (Fig. 5), suggesting that 3PP meditation disrupts multisensory processes of the full-body illusion, especially during asynchronous stroking that are overcome by heightened sensitivity during synchronous stroking. As reported previously for meditation practice, the present 3PP condition also led to a more transparent body boundary and the magnitude of these changes between conditions positively correlated with the self-identification changes in the illusion-inducing synchronous condition. These findings further associate the perceived transparency of the body boundary to a classical measure of multisensory own body perception (full-body illusion) and more generally link the minimal self, as studied in cognitive neuroscience, to meditation practice, extending previous data using questionnaires and detailed verbal interviews (Berkovich-Ohana et al., 2020; Nave et al., 2021).

4.3. More negative heartbeat evoked response in 3PP meditation

Neural responses time-locked to heartbeats, HEPs, have been shown to reflect changes in self-identification induced by visuo-tactile stimulation (Park et al., 2016). Here we report that both conditions showed prominent HEPs characterized by typical topography and that the HEP in the 3PP versus 1PP meditation condition (associated with decreased self-identification) showed a more negative HEP. HEP decrease has been observed in the full-body illusion, during asynchronous visuo-tactile stimulation and was associated with decreased self-identification as the present 3PP condition (Park et al., 2016). This previous work, however, did not investigate meditation practice. HEP changes have further been associated with visual consciousness (Park and Tallon-Baudry, 2014), narrative self (Babo-Rebelo et al., 2016), and long-term meditation practice (i.e. greater HEP amplitudes in Tibetan Buddhist meditators versus controls) (Jiang et al., 2020). Methodologically, we suggest that HEPs are an interesting neuromarker for meditation research, because it can be acquired during meditation practice without exposing practitioners to additional sensory stimulation or cognitive load, often required by other evoked potentials (i.e., Chan et al., 2020; Singh and Telles, 2015).

Concerning HEP topography and its neural sources, our data highlighted fronto-central regions showing 1PP-3PP differences, aligning with meta-analytical HEP data (Coll et al., 2021) that arguably reflect the involvement of PCC and interoceptive cortices (Al et al., 2021; Gentsch et al., 2019; Hodossy et al., 2021; Kumral et al., 2022). The PCC has been associated with self-referential processing (Agathos et al., 2023; Brewer et al., 2013; Leech & Sharp, 2014; Parvizi et al., 2021) and the minimal self (Lyu et al., 2023; Park et al., 2016; Vesuna et al., 2020). The PCC is also commonly activated across various meditation practices (Brewer and Garrison, 2014; Kral et al., 2019; T.R.A. 2022; Zsadanyi et al., 2021), and has been consistently linked to the HEP (Jiang et al., 2020). Furthermore, the PCC has been recently associated with the experience of ‘boundarylessness’ (Dor-Ziderman et al., 2016; Lindström et al., 2023), a meditation experience that parallels the perceived body boundary changes reported in our study. Additional activation was observed in the mPFC in the 3PP versus 1PP condition, consistent with the role of this region in self-referential processing (i.e., Qin et al., 2020).

4.4. Limitations

While the proposed meditation protocol demonstrates consistent changes in the sense of self including the subjective perceived body

boundary, the full body illusion, and the processing of interoceptive bodily signals (HEP), several limitations should be acknowledged. First, the study examined a homogeneous sample of individuals without prior meditation experience, which strengthens its internal validity by minimizing the variability of prior meditation practices, but also limits the generalizability of the current protocol to the larger field of meditation and experienced meditators in particular. For example, Vipassana practitioners have been reported to experience changes in their self-concept (Emavardhana and Tori, 1997) and self-related processing (Shi & He, 2021). It is an intriguing possibility to assess whether the modulation of the minimal self during a VR meditation protocol may support or even facilitate the cultivation of such changes in experienced practitioners. It also remains to be explored how variations in meditation practices and mindfulness traits of the meditators may modulate some of the observed effects of the proposed meditation protocol. Finally, we note that the present VR meditation was a first design and that the flexibility and programmability of the VR protocol will allow many adaptations of the VR protocol, integrating it more fully with certain practices, but also to individual meditators (personalization).

Second, although visual and auditory (non-verbal) stimuli in the VR scene were identical (except changes of viewpoint at the end of the meditation session), we note that there were differences in the verbal guidance, specifically related to the perspective shift. Thus, in the last phase of the meditation, participants are instructed to focus on an object in the virtual scene which was different in the two conditions: a pile of rocks in the 1PP condition, and the avatar in the 3PP condition. Therefore, we cannot exclude the possibility that differences in verbal guidance in addition to the perceptual perspective shift may have affected responses to the FBI, the PBB, OBE-like sensations, and HEP. Moreover, we only acquired a baseline value for the PBB score, which consolidated the meditation effect (baseline against post-tests after both 1PP and 3PP). Baseline values were not acquired for the other measures. This choice was taken to avoid carry-over effects in the within-subject design, particularly for the full-body illusion, which includes prominent 3PP exposure during visuo-tactile stroking and may have biased responses when perspective shifted during the meditation session.

Additionally, the current study did not test whether the observed changes in the sense of self persist over time and whether there is a long-term effect on the sense of self after intensive training of the novel meditation used in this study. Future research incorporating experienced meditators and long-term meditation training could provide a more comprehensive understanding of the altered sense of self and the effectiveness of the current meditation protocol.

To summarize, the present 3PP practice – meditating while perceiving the world and one’s body from a distanced backward shifted third-person viewpoint — induces immediate effects on disembodiment, a less clearly experienced body boundary, and decreased self-identification with one’s body that depends on the synchrony of visuo-tactile stimulation. The link between self-identification and perceived body boundary following 3PP meditation was corroborated by our additional finding that the PBBQ decrease between conditions positively correlated with the self-identification changes in the full-body-illusion-inducing synchronous condition, linking the perceived salience of the body boundary to a measure of the minimal self. These subjective-behavioral changes were also reflected in HEP-related differential activation of PCC and mPFC. Using a VR-supported meditation platform and methodologies, our study reveals novel connections between the sense of self in meditation practice and the neuroscience of the multisensory bodily self, reflected in subjective and behavioral changes in multisensory own body perception, and associated interoceptive bodily processes. The current meditation protocol demonstrates short-term effects and lays a promising foundation for future research on meditation-induced long-term changes in the sense of self.

CRedit authorship contribution statement

Hang Yang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bruno Herbelin:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Data curation, Conceptualization. **Chuong Ngo:** Methodology, Investigation. **Loup Vuarnesson:** Visualization, Software, Methodology, Investigation. **Olaf Blanke:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

O.B. and B.H. are inventors on patent US17/288,598 (Title: Method and system for creating an out-of-body experience) held by the Swiss Federal Institute (EPFL) C.N. and L.V. are employees of Company All Here SA The other authors declare no other competing interests.

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Data availability

Data will be made available on request.

References

- Ader, N.E., 1973. Impact of prior sets given experimenters and subjects on the experimenter expectancy effect. *Sociometry*. 36 (1), 113. <https://doi.org/10.2307/2786286>.
- Al, E., Iliopoulos, F., Nikulin, V.V., Villringer, A., 2021. Heartbeat and somatosensory perception. *Neuroimage* 238, 118247. <https://doi.org/10.1016/j.neuroimage.2021.118247>.
- Albahari, M., 2006. The two-tiered illusion of self. In: Albahari, M. (Ed.), *Analytical Buddhism: The Two-tiered Illusion of Self*. Palgrave Macmillan, UK, pp. 193–205. https://doi.org/10.1057/9780230800540_10.
- Albert, L., Lance, F., Dubessy, M., Herbelin, B., Reymond, G., & Blanke, O. (2019). Real-time 360 body scanning system for virtual reality research applications. *10th Int. Conference and Exhibition on 3D Body Scanning and Processing Technologies*, Lugano, Switzerland, 150–157. <https://doi.org/10.15221/19.150>.
- Análayo, B., 2019. Meditation on the breath: mindfulness and focused attention. *Mindfulness* 10 (8), 1684–1691. <https://doi.org/10.1007/s12671-019-01169-9>.
- Aspell, J.E., Lenggenhager, B., Blanke, O., 2009. Keeping in touch with one's self: multisensory mechanisms of self-consciousness. *PLoS One* 4 (8), e6488. <https://doi.org/10.1371/journal.pone.0006488>.
- Ataria, Y., Dor-Ziderman, Y., Berkovich-Ohana, A., 2015. How does it feel to lack a sense of boundaries? A case study of a long-term mindfulness meditator. *Conscious. Cogn.* 37, 133–147. <https://doi.org/10.1016/j.concog.2015.09.002>.
- Babo-Rebello, M., Richter, C.G., Tallon-Baudry, C., 2016. Neural responses to heartbeats in the default network encode the self in spontaneous thoughts. *J. Neurosci.* 36 (30), 7829–7840. <https://doi.org/10.1523/JNEUROSCI.0262-16.2016>.

- Barr, D.J., Levy, R., Scheepers, C., Tily, H.J., 2013. Random effects structure for confirmatory hypothesis testing: keep it maximal. *J. Mem. Lang.* 68 (3), 255–278. <https://doi.org/10.1016/j.jml.2012.11.001>.
- Bayer, M., Betka, S., Herbelin, B., Blanke, O., Zimmermann, E., 2023. The full-body illusion changes visual depth perception. *Sci. Rep.* 13 (1). <https://doi.org/10.1038/s41598-023-37715-8>. Article 1.
- Bennett, M.P., Knight, R., Patel, S., So, T., Dunning, D., Barnhofer, T., Smith, P., Kuyken, W., Ford, T., Dalgleish, T., 2021. Decentering as a core component in the psychological treatment and prevention of youth anxiety and depression: a narrative review and insight report. *Transl. Psychiatry* 11 (1), 1–14. <https://doi.org/10.1038/s41398-021-01397-5>.
- Berkovich-Ohana, A., Dor-Ziderman, Y., Trautwein, F.-M., Schweitzer, Y., Nave, O., Fulder, S., Ataria, Y., 2020. The Hitchhiker's Guide to neurophenomenology – The case of studying self boundaries with meditators. *Front. Psychol.* 11. <https://www.frontiersin.org/articles/10.3389/fpsyg.2020.01680>.
- Biran, A., Jeremic, A., 2023. The feasibility of Human identification from multiple ECGs using maximal overlap discrete wavelet transform (MODWT) and weighted majority voting method (WMVM). *Digital Med. Healthcare Technol.* 2. <https://doi.org/10.5772/dmht.13>.
- Blanke, O., Landis, T., Spinelli, L., Seeck, M., 2004. Out-of-body experience and autopsy of neurological origin. *Brain* 127 (2), 243–258. <https://doi.org/10.1093/brain/awh040>.
- Blanke, O., Mohr, C., Michel, C.M., Pascual-Leone, A., Brugger, P., Seeck, M., Landis, T., Thut, G., 2005. Linking out-of-body experience and self processing to mental own-body imagery at the temporoparietal junction. *J. Neurosci.* 25 (3), 550–557. <https://doi.org/10.1523/JNEUROSCI.2612-04.2005>.
- Blanke, O., Ortigue, S., Landis, T., Seeck, M., 2002. Stimulating illusory own-body perceptions. *Nature* 419 (6904), 269–270. <https://doi.org/10.1038/419269a>.
- Blanke, O., Slater, M., Serino, A., 2015. Behavioral, neural, and computational principles of bodily self-consciousness. *Neuron* 88 (1), 145–166. <https://doi.org/10.1016/j.neuron.2015.09.029>.
- Braithwaite, J.J., Samson, D., Apperly, I., Brogna, E., Hulleman, J., 2011. Cognitive correlates of the spontaneous out-of-body experience (OBE) in the psychologically normal population: evidence for an increased role of temporal-lobe instability, body-distortion processing, and impairments in own-body transformations. *Cortex* 47 (7), 839–853. <https://doi.org/10.1016/j.cortex.2010.05.002>.
- Brandmeyer, T., Delorme, A., 2018. Reduced mind wandering in experienced meditators and associated EEG correlates. *Exp. Brain Res.* 236 (9), 2519–2528. <https://doi.org/10.1007/s00221-016-4811-5>.
- Brewer, J.A., Garrison, K.A., 2014. The posterior cingulate cortex as a plausible mechanistic target of meditation: findings from neuroimaging. *Ann. NY Acad. Sci.* 1307 (1), 19–27. <https://doi.org/10.1111/nyas.12246>.
- Britton, W.B., Desbordes, G., Acabchuk, R., Peters, S., Lindahl, J.R., Canby, N.K., Vago, D.R., Dumais, T., Lipsky, J., Kimmel, H., Sager, L., Rahrigh, H., Cheaito, A., Acero, P., Scharf, J., Lazar, S.W., Schuman-Olivier, Z., Ferrer, R., Moitra, E., 2021. From self-esteem to selflessness: an evidence (Gap) map of self-related processes as mechanisms of mindfulness-based interventions. *Front. Psychol.* 12, 730972. <https://doi.org/10.3389/fpsyg.2021.730972>.
- Canby, N.K., Lindahl, J., Britton, W.B., Córdova, J.V., 2024. Clarifying and measuring the characteristics of experiences that involve a loss of self or a dissolution of its boundaries. *Conscious. Cogn.* 119, 103655. <https://doi.org/10.1016/j.concog.2024.103655>.
- Chan, R.W., Alday, P.M., Zou-Williams, L., Lushington, K., Schlesewsky, M., Bornkessel-Schlesewsky, I., Immink, M.A., 2020. Focused-attention meditation increases cognitive control during motor sequence performance: evidence from the N2 cortical evoked potential. *Behav. Brain Res.* 384, 112536. <https://doi.org/10.1016/j.bbr.2020.112536>.
- Coll, M.-P., Hobson, H., Bird, G., Murphy, J., 2021. Systematic review and meta-analysis of the relationship between the heartbeat-evoked potential and interoception. *Neurosci. Biobehav. Rev.* 122, 190–200. <https://doi.org/10.1016/j.neubiorev.2020.12.012>.
- Curtin, F., Schulz, P., 1998. Multiple correlations and bonferroni's correction. *Biol. Psychiatry* 44 (8), 775–777. [https://doi.org/10.1016/S0006-3223\(98\)00043-2](https://doi.org/10.1016/S0006-3223(98)00043-2).
- Dahl, C.J., Lutz, A., Davidson, R.J., 2015. Reconstructing and deconstructing the self: cognitive mechanisms in meditation practice. *Trends Cogn. Sci.* 19 (9), 515–523. <https://doi.org/10.1016/j.tics.2015.07.001>.
- Dahl, C.J., Wilson-Mendenhall, C.D., Davidson, R.J., 2020. The plasticity of well-being: a training-based framework for the cultivation of human flourishing. *Proc. Natl. Acad. Sci.* 117 (51), 32197–32206. <https://doi.org/10.1073/pnas.2014859117>.
- Damasio, A.R., 1999. *How the brain creates the mind*. *Sci. Am.* 281 (6), 112–117.
- Dambrun, M., 2016. When the dissolution of perceived body boundaries elicits happiness: the effect of selflessness induced by a body scan meditation. *Conscious. Cogn.* 46, 89–98. <https://doi.org/10.1016/j.concog.2016.09.013>.
- Dambrun, M., Bernard, A., Didelot, T., Chaulet, M., Droit-Volet, S., Corman, M., Juneau, C., Martinon, L.M., 2019. Unified consciousness and the effect of body scan meditation on happiness: alteration of inner-body experience and feeling of harmony as central processes. *Mindfulness* 10 (8), 1530–1544. <https://doi.org/10.1007/s12671-019-01104-y>.
- Dambrun, M., Martinon, L., Juneau, C., Droit-Volet, S., Corman, M., De Oliveira, P., Pellerin, N., 2023. Changes in self-location during the practice of mindfulness meditation in novices. *Mindfulness* 14 (1), 174–191. <https://doi.org/10.1007/s12671-022-02042-y>.
- Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J. Neurosci. Methods* 134 (1), 9–21. <https://doi.org/10.1016/j.jneumeth.2003.10.009>.

- Dor-Ziderman, Y., Ataria, Y., Fulder, S., Goldstein, A., Berkovich-Ohana, A., 2016. Self-specific processing in the meditating brain: a MEG neurophenomenology study. *Neurosci. Conscious.* (1). <https://doi.org/10.1093/NC/NW019>, 2016.
- Dor-Ziderman, Y., Berkovich-Ohana, A., Glicksohn, J., Goldstein, A., 2013. Mindfulness-induced selflessness: a MEG neurophenomenological study. *Front. Hum. Neurosci.* 7. <https://doi.org/10.3389/fnhum.2013.00582>.
- Droit-Volet, S., Damburn, M., 2019. Awareness of the passage of time and self-consciousness: what do meditators report? *Psych. J.* 8 (1), 51–65. <https://doi.org/10.1002/pchj.270>.
- Dunne, J., 2011. Toward an understanding of non-dual mindfulness. *Contemp. Buddhism* 12 (1), 71–88. <https://doi.org/10.1080/14639947.2011.564820>.
- Emavardhana, T., Tori, C.D., 1997. Changes in self-concept, ego defense mechanisms, and religiosity following seven-day Vipassana meditation retreats. *J. Sci. Study Relig.* 36 (2), 194–206. <https://doi.org/10.2307/1387552>.
- Ehrsson, H.H., 2007. The experimental induction of out-of-body experiences. *Science* 317 (5841), 1048. https://doi.org/10.1126/SCIENCE.1142175/SUPPL_FILE/EHRSSON.SOM.PDF.
- Farb, N.A.S., Segal, Z.V., Mayberg, H., Bean, J., McKeon, D., Fatima, Z., Anderson, A.K., 2007. Attending to the present: mindfulness meditation reveals distinct neural modes of self-reference. *Soc. Cogn. Affect. Neurosci.* 2 (4), 313–322. <https://doi.org/10.1093/scan/nsm030>.
- Faul, F., Erdfelder, E., Lang, A.-G., Buchner, A., 2007. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39 (2), 175–191. <https://doi.org/10.3758/BF03193146>.
- Feldman, G., Hayes, A., Kumar, S., Greeson, J., Laurenceau, J.-P., 2007. Mindfulness and emotion regulation: the development and initial validation of the cognitive and affective Mindfulness scale-revised (CAMS-R). *J. Psychopathol. Behav. Assess.* 29 (3), 177–190. <https://doi.org/10.1007/s10862-006-9035-8>.
- Feldman, G., Westine, M., Edelman, A., Higgins, M., Renna, M., Greeson, J., 2022. Cognitive and Affective Mindfulness scale-revised (CAMS-R). In: Medvedev, O.N., Krägeloh, C.U., Siegert, R.J., Singh, N.N. (Eds.), *Handbook of Assessment in Mindfulness Research*. Springer International Publishing, pp. 1–24. https://doi.org/10.1007/978-3-030-77644-2_19-1.
- Fukushima, H., Terasawa, Y., Umeda, S., 2011. Association between interoception and empathy: evidence from heartbeat-evoked brain potential. *Int. J. Psychophysiol.* 79 (2), 259–265. <https://doi.org/10.1016/j.ijpsycho.2010.10.015>.
- Gallagher, S., 2000. Philosophical conceptions of the self: implications for cognitive science. *Trends Cogn. Sci.* 4 (1), 14–21. [https://doi.org/10.1016/S1364-6613\(99\)01417-5](https://doi.org/10.1016/S1364-6613(99)01417-5).
- Gan, R., Zhang, L., Chen, S., 2022. The effects of body scan meditation: a systematic review and meta-analysis. *Appl. Psychol.* 14 (3), 1062–1080. <https://doi.org/10.1111/aphw.12366>.
- Gecht, J., Kessel, R., Forkmann, T., Gauggel, S., Druke, B., Scherer, A., Mainz, V., 2014. A mediation model of mindfulness and decentering: sequential psychological constructs or one and the same? *BMC. Psychol.* 2 (1), 18. <https://doi.org/10.1186/2050-7283-2-18>.
- Gentsch, A., Sel, A., Marshall, A.C., Schütz-Bosbach, S., 2019. Affective interoceptive inference: evidence from heart-beat evoked brain potentials. *Hum. Brain Mapp.* 40 (1), 20–33. <https://doi.org/10.1002/hbm.24352>.
- Gramfort, A., Papadopoulos, T., Olivi, E., Clerc, M., 2010. OpenMEEG: opensource software for quasistatic bioelectromagnetics. *Biomed. Eng. Online* 9 (1), 45. <https://doi.org/10.1186/1475-925X-9-45>.
- Hanley, A.W., Damburn, M., Garland, E.L., 2020. Effects of mindfulness meditation on self-transcendent states: perceived body boundaries and spatial frames of reference. *Mindfulness* 11 (5), 1194–1203. <https://doi.org/10.1007/s12671-020-01330-9>.
- Hiroimitsu, K., Shinoura, N., Yamada, R., Midorikawa, A., 2020. Dissociation of the subjective and objective bodies: out-of-body experiences following the development of a posterior cingulate lesion. *J. Neuropsychol.* 14 (1), 183–192. <https://doi.org/10.1111/jnp.12199>.
- Hodossy, L., Ainley, V., Tsakiris, M., 2021. How do we relate to our heart? Neurobehavioral differences across three types of engagement with cardiac interoception. *Biol. Psychol.* 165, 108198. <https://doi.org/10.1016/j.biopsycho.2021.108198>.
- 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. <https://doi.org/10.1177/1745691611419671>.
- Ionta, S., Heydrich, L., Lenggenhager, B., Mouthon, M., Fornari, E., Chapuis, D., Gassert, R., Blanke, O., 2011. Multisensory mechanisms in temporoparietal cortex support self-location and first-person perspective. *Neuron* 70 (2), 363–374. <https://doi.org/10.1016/j.neuron.2011.03.009>.
- Jiang, H., He, B., Guo, X., Wang, X., Guo, M., Wang, Z., Xue, T., Li, H., Xu, T., Ye, S., Suma, D., Tong, S., Cui, D., 2020. Brain-Heart interactions underlying traditional Tibetan Buddhist Meditation. *Cerebral Cortex* 30 (2), 439–450. <https://doi.org/10.1093/cercor/bhz095>.
- Katyal, S., Goldin, P., 2021. Alpha and theta oscillations are inversely related to progressive levels of meditation depth. *Neurosci. Conscious.* (1), 2021. <https://doi.org/10.1093/nc/niab042>.
- Kessel, R., Gecht, J., Forkmann, T., Druke, B., Gauggel, S., Mainz, V., 2016. Exploring the relationship of decentering to health related concepts and cognitive and metacognitive processes in a student sample. *BMC. Psychol.* 4 (1), 11. <https://doi.org/10.1186/s40359-016-0115-6>.
- Kraehennann, R., Pokorny, D., Aicher, H., Preller, K.H., Pokorny, T., Bosch, O.G., Seifritz, E., Vollenweider, F.X., 2017. LSD increases primary process thinking via serotonin 2A receptor activation. *Front. Pharmacol.* 8, 814. <https://doi.org/10.3389/fphar.2017.00814>.
- III Kral, T.R.A., Imhoff-Smith, T., Dean, D.C., Grupe, D., Adluru, N., Patsenko, E., Mumford, J.A., Goldman, R., Rosenkranz, M.A., Davidson, R.J., 2019. Mindfulness-based Stress reduction-related changes in posterior cingulate resting brain connectivity. *Soc. Cogn. Affect. Neurosci.* 14 (7), 777–787. <https://doi.org/10.1093/scan/nsz050>.
- Kral, T.R.A., Lapate, R.C., Imhoff-Smith, T., Patsenko, E., Grupe, D.W., Goldman, R., Rosenkranz, M.A., Davidson, R.J., 2022. Long-term meditation training is associated with enhanced subjective attention and stronger posterior cingulate–Rostrolateral prefrontal cortex resting connectivity. *J. Cogn. Neurosci.* 34 (9), 1576–1589. https://doi.org/10.1162/jocn_a.01881.
- Kumar, P., Das, A.K., Halder, S., 2020. Respiration rate variability analysis under different body postures, 2020 IEEE-HYDCON 1–4. <https://doi.org/10.1109/HYDCON48903.2020.9242875>.
- Kumral, D., Al, E., Cesnaite, E., Kornej, J., Sander, C., Hensch, T., Zeynalova, S., Tautenhahn, S., Hagendorf, A., Laufs, U., Wächter, R., Nikulin, V., Villringer, A., 2022. Attenuation of the heartbeat-evoked potential in patients with atrial fibrillation. *JACC* 8 (10), 1219–1230. <https://doi.org/10.1016/j.jacep.2022.06.019>.
- Lee, D.J., Kulubya, E., Goldin, P., Goodarzi, A., Girgis, F., 2018. Review of the neural oscillations underlying meditation. *Front. Neurosci.* 12. <https://www.frontiersin.org/articles/10.3389/fnins.2018.00178>.
- Legrand, D., Ruby, P., 2009. What is self-specific? Theoretical investigation and critical review of neuroimaging results. *Psychol. Rev.* 116 (1), 252–282. <https://doi.org/10.1037/a0014172>.
- Lenggenhager, B., Mouthon, M., Blanke, O., 2009. Spatial aspects of bodily self-consciousness. *Conscious. Cogn.* 18 (1), 110–117. <https://doi.org/10.1016/j.concog.2008.11.003>.
- Lenggenhager, B., Tadi, T., Metzinger, T., Blanke, O., 2007. Video Ergo Sum: manipulating bodily self-consciousness. *Science* 317 (5841), 1096–1099. <https://doi.org/10.1126/science.1143439>.
- Linares Gutiérrez, D., Schmidt, S., Meissner, K., Wittmann, M., 2022. Changes in subjective time and self during meditation. *Biology* 11 (8), 1116. <https://doi.org/10.3390/biology11081116>.
- Lindah, J.R., Britton, W.B., 2019. I have this feeling of not really being here”: buddhist meditation and changes in sense of self. *J. Consciousness Stud.* 26 (7–8), 158–183.
- Lindström, L., Goldin, P., Mårtensson, J., Cardena, E., 2023. Nonlinear brain correlates of trait self-boundariness. *Neurosci. Conscious.* 2023 (1), niad006. <https://doi.org/10.1093/nc/niad006>.
- Lomas, T., Ivtzan, I., Fu, C.H.Y., 2015. A systematic review of the neurophysiology of mindfulness on EEG oscillations. *Neurosci. Biobehav. Rev.* 57, 401–410. <https://doi.org/10.1016/j.neubiorev.2015.09.018>.
- Lutz, A., Jha, A.P., Dunne, J.D., Saron, C.D., 2015. Investigating the phenomenological matrix of mindfulness-related practices from a neurocognitive perspective. *Am. Psychol.* 70 (7), 632–658. <https://doi.org/10.1037/a0039585>.
- Lutz, A., Slagter, H.A., Dunne, J.D., Davidson, R.J., 2008. Attention regulation and monitoring in meditation. *Trends Cogn. Sci.* 12 (4), 163–169. <https://doi.org/10.1016/j.tics.2008.01.005>.
- Lyu, D., Steiger, J.R., Xin, C., Ma, E., Lusk, Z., Aparicio, M.K., Werbaneth, K., Perry, C.M., Deisseroth, K., Buch, V., Parvizi, J., 2023. Causal evidence for the processing of bodily self in the anterior preuncus. *Neuron* 111 (16), 2502–2512. <https://doi.org/10.1016/j.neuron.2023.05.013> e4.
- Millière, R., Carhart-Harris, R.L., Roseman, L., Trautwein, F.-M., Berkovich-Ohana, A., 2018. Psychedelics, meditation, and self-consciousness. *Front. Psychol.* 9. <https://doi.org/10.3389/fpsyg.2018.01475>.
- Milne, E., Dunn, S., Zhao, C., Jones, M., 2019. Altered neural dynamics in people who report spontaneous out of body experiences. *Cortex* 111, 87–99. <https://doi.org/10.1016/j.cortex.2018.10.019>.
- Moon, H.-J., Albert, L., De Falco, E., Tasu, C., Gauthier, B., Park, H.-D., Blanke, O., 2024. Changes in spatial self-consciousness elicit grid cell-like representation in the entorhinal cortex. *Proc. Natl. Acad. Sci.* 121 (12), e2315758121. <https://doi.org/10.1073/pnas.2315758121>.
- Morey, R.D., Rouder, J.N., Pratte, M.S., Speckman, P.L., 2011. Using MCMC chain outputs to efficiently estimate Bayes factors. *J. Math. Psychol.* 55 (5), 368–378. <https://doi.org/10.1016/j.jmp.2011.06.004>.
- Nakul, E., Orlando-Dessaints, N., Lenggenhager, B., Lopez, C., 2020. Measuring perceived self-location in virtual reality. *Sci. Rep.* 10 (1), 6802. <https://doi.org/10.1038/s41598-020-63643-y>.
- Nave, O., Trautwein, F.-M., Ataria, Y., Dor-Ziderman, Y., Schweitzer, Y., Fulder, S., Berkovich-Ohana, A., 2021. Self-boundary dissolution in meditation: a phenomenological investigation. *Brain Sci.* 11 (6), 819. <https://doi.org/10.3390/brainsci11060819>.
- Nicolò, A., Massaroni, C., Schena, E., Sacchetti, M., 2020. The importance of Respiratory rate monitoring: from healthcare to sport and exercise. *Sensors* 20 (21), 6396. <https://doi.org/10.3390/s20216396>.
- Nikitin, J., Freund, A.M., 2021. Does focusing on others enhance subjective well-being? The role of age, motivation, and relationship closeness. *Psychol. Aging* 36 (1), 69–82. <https://doi.org/10.1037/pag0000489>.
- Noel, J.-P., Pfeiffer, C., Blanke, O., Serino, A., 2015. Peripersonal space as the space of the bodily self. *Cognition* 144, 49–57. <https://doi.org/10.1016/j.cognition.2015.07.012>.
- Northoff, G., Heinzl, A., De Greck, M., Bermpohl, F., Dobrowolny, H., Panksepp, J., 2006. Self-referential processing in our brain—A meta-analysis of imaging studies on the self. *Neuroimage* 31 (1), 440–457. <https://doi.org/10.1016/j.neuroimage.2005.12.002>.
- Noto, T., Zhou, G., Schuele, S., Templer, J., Zelano, C., 2018. Automated analysis of breathing waveforms using BreathMetrics: a respiratory signal processing toolbox. *Chem. Senses* 43 (8), 583–597. <https://doi.org/10.1093/chemse/bjy045>.

- Oostenvelde, R., Fries, P., Maris, E., Schoffelen, J.-M., 2011. FieldTrip: open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Comput. Intell. Neurosci.* 2011, 156869. <https://doi.org/10.1155/2011/156869>.
- Oostenvelde, R., Praamstra, P., 2001. The five percent electrode system for high-resolution EEG and ERP measurements. *Clinic. Neurophysiol.* 112 (4), 713–719. [https://doi.org/10.1016/S1388-2457\(00\)00527-7](https://doi.org/10.1016/S1388-2457(00)00527-7).
- Park, H.-D., Bernasconi, F., Bello-Ruiz, J., Pfeiffer, C., Salomon, R., Blanke, O., 2016. Transient modulations of neural responses to heartbeats covary with bodily self-consciousness. *J. Neurosci.* 36 (32), 8453–8460. <https://doi.org/10.1523/JNEUROSCI.0311-16.2016>.
- Park, H.-D., Bernasconi, F., Salomon, R., Tallon-Baudry, C., Spinelli, L., Seeck, M., Schaller, K., Blanke, O., 2018. Neural sources and underlying mechanisms of Neural responses to heartbeats, and their role in bodily self-consciousness: an intracranial EEG study. *Cerebral Cortex* 28 (7), 2351–2364. <https://doi.org/10.1093/cercor/bhx136>.
- Park, H.-D., Blanke, O., 2019. Heartbeat-evoked cortical responses: underlying mechanisms, functional roles, and methodological considerations. *Neuroimage* 197, 502–511. <https://doi.org/10.1016/j.neuroimage.2019.04.081>.
- Park, H.-D., Tallon-Baudry, C., 2014. The neural subjective frame: from bodily signals to perceptual consciousness. *Philos. Trans. R. Soc. B Biol. Sci.* 369 (1641), 20130208. <https://doi.org/10.1098/rstb.2013.0208>.
- Pernet, C.R., Chauveau, N., Gaspar, C., Rousselet, G.A., 2011. LIMO EEG: a toolbox for hierarchical Linear Modeling of ElectroEncephaloGraphic data. *Comput. Intell. Neurosci.* 2011, 1–11. <https://doi.org/10.1155/2011/831409>.
- Qin, P., Wang, M., Northoff, G., 2020. Linking bodily, environmental and mental states in the self—A three-level model based on a meta-analysis. *Neurosci. Biobehav. Rev.* 115, 77–95. <https://doi.org/10.1016/j.neubiorev.2020.05.004>.
- Rosenthal, R., Fode, K.L., 1963. Psychology of the scientist: V. Three experiments in experimenter bias. *Psychol. Rep.* 12 (2), 491–511. <https://doi.org/10.2466/pr0.1963.12.2.491>.
- Salomon, R., Fernandez, N.B., Van Elk, M., Vachicouras, N., Sabatier, F., Tychinskaya, A., Llobera, J., Blanke, O., 2016. Changing motor perception by sensorimotor conflicts and body ownership. *Sci. Rep.* 6 (1), 25847. <https://doi.org/10.1038/srep25847>.
- Schmidt, T.T., Berkemeyer, H., 2018. The Altered States Database: psychometric data of altered states of consciousness. *Front. Psychol.* 9. <https://www.frontiersin.org/articles/10.3389/fpsyg.2018.01028>.
- Seth, A.K., Tsakiris, M., 2018. Being a beast machine: the somatic basis of selfhood. *Trends Cogn. Sci.* 22 (11), 969–981. <https://doi.org/10.1016/j.tics.2018.08.008>.
- Shaffer, F., Ginsberg, J.P., 2017. An overview of heart rate variability metrics and norms. *Front. Public Health* 5, 258. <https://doi.org/10.3389/fpubh.2017.00258>.
- Siderits, M., Thompson, E., Zahavi, D., 2011. *Self, No Self?: Perspectives from Analytical, Phenomenological, and Indian Traditions.* Oxford University Press.
- Singh, N., Telles, S., 2015. Neurophysiological effects of meditation based on evoked and event related potential recordings. *Biomed. Res. Int.* 2015, 1–11. <https://doi.org/10.1155/2015/406261>.
- Song, M.S. (2020). *Flight of mind: sensorimotor and multisensory embodiment with aviation robotics, flight simulator, and virtual reality.* <https://doi.org/10.5075/EPFL-THESIS-7965>.
- Soni, R., Muniyandi, M., 2019. Breath rate variability: a novel measure to study the meditation effects. *Int. J. Yoga* 12 (1), 45–54. https://doi.org/10.4103/ijoy.IJOY_27_17.
- Tadel, F., Baillet, S., Mosher, J.C., Pantazis, D., Leahy, R.M., 2011. Brainstorm: a user-friendly application for MEG/EEG analysis. *Comput. Intell. Neurosci.* 2011, 1–13. <https://doi.org/10.1155/2011/879716>.
- Tanaka, Y., Ito, Y., Terasawa, Y., Umeda, S., 2023. Modulation of heartbeat-evoked potential and cardiac cycle effect by auditory stimuli. *Biol. Psychol.* 182, 108637. <https://doi.org/10.1016/j.biopsycho.2023.108637>.
- Tang, Y.-Y., Hölzel, B.K., Posner, M.I., 2015. The neuroscience of mindfulness meditation. *Nat. Rev. Neurosci.* 16 (4), 213–225. <https://doi.org/10.1038/nrn3916>.
- Terhaar, J., Viola, F.C., Bär, K.-J., Debener, S., 2012. Heartbeat evoked potentials mirror altered body perception in depressed patients. *Clinic. Neurophysiol.* 123 (10), 1950–1957. <https://doi.org/10.1016/j.clinph.2012.02.086>.
- Trautwein, F.-M., Schweitzer, Y., Dor-Ziderman, Y., Nave, O., Ataria, Y., Fulder, S., Berkovich-Ohana, A., 2024. Suspending the embodied self in meditation attenuates beta oscillations in the posterior medial cortex. *J. Neurosci.* 44 (26). <https://doi.org/10.1523/JNEUROSCI.1182-23.2024>.
- Vago, D.R., Silbersweig, D.A., 2012. Self-awareness, self-regulation, and self-transcendence (S-ART): a framework for understanding the neurobiological mechanisms of mindfulness. *Front. Hum. Neurosci.* 6. <https://doi.org/10.3389/fnhum.2012.00296>.
- Vago, D.R., Zeidan, F., 2016. The brain on silent: mind wandering, mindful awareness, and states of mental tranquility. *Ann. NY Acad. Sci.* 1373 (1), 96–113. <https://doi.org/10.1111/nyas.13171>.
- Vesuna, S., Kauvar, I.V., Richman, E., Gore, F., Oskotsky, T., Sava-Segal, C., Luo, L., Malenka, R.C., Henderson, J.M., Nuyujukian, P., Parvizi, J., Deisseroth, K., 2020. Deep posteromedial cortical rhythm in dissociation. *Nature* 586 (7827), 87–94. <https://doi.org/10.1038/s41586-020-2731-9>.
- Vuarnesson, L., Herbelin, B., Blanke, O., 2024. Virtual reality for inward contemplation. *ACM SIGGRAPH 2024 Talks* 1–2. <https://doi.org/10.1145/3641233.3664341>.
- Wu, H.-P., Nakul, E., Betka, S., Lance, F., Herbelin, B., Blanke, O., 2023. Out-of-body illusion induced by visual-vestibular stimulation. *iScience*, 108547. <https://doi.org/10.1016/j.isci.2023.108547>.
- Xu, H., Ebrahim, M.P., Hasan, K., Heydari, F., Howley, P., Yuce, M.R., 2021. Accurate heart rate and respiration rate detection based on a higher-order harmonics peak selection method using radar non-contact sensors. *Sensors* 22 (1), 83. <https://doi.org/10.3390/s22010083>.
- Zsadanyi, S.E., Kurth, F., Luders, E., 2021. The effects of mindfulness and meditation on the cingulate cortex in the healthy Human brain: a review. *Mindfulness* 12 (10), 2371–2387. <https://doi.org/10.1007/s12671-021-01712-7>.