Self-specific processing in the meditating brain: a MEG neurophenomenology study

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Abstract

Self-specific processes (SSPs) specify the self as an embodied subject and agent, implementing a functional self/nonself distinction in perception, cognition, and action. Despite recent interest, it is still undetermined whether SSPs are all-or-nothing or graded phenomena; whether they can be identified in neuroimaging data; and whether they can be altered through attentional training. These issues are approached through a neurophenomenological exploration of the sense-of-boundaries (SB), the fundamental experience of being an ‘I’ (self) separated from the ‘world’ (nonself). The SB experience was explored in collaboration with a uniquely qualified meditation practitioner, who volitionally produced, while being scanned by magnetoencephalogram (MEG), three mental states characterized by a graded SB experience. The results were then partly validated in an independent group of 10 long-term meditators. Implicated neural mechanisms include right-lateralized beta oscillations in the temporo-parietal junction, a region known to mediate the experiential unity of self and body; and in the medial parietal cortex, a central node of the self’s representational system. The graded nature as well as the trainable flexibility and neural plasticity of SSPs may hold clinical implications for populations with a disturbed SB.

Key words: self-specific processes; minimal self; MEG; neurophenomenology; meditation; beta band; parietal cortex

Introduction

In the last decade, cognitive neuroscience has widened its exploration of the neural processes giving rise to self-experience from processes that evaluate certain features in relation to one’s perceptual image or mental concept of oneself (self-related processes, SRP), to processes that specify the self as an embodied subjective knower and agent (self-specific processes, SSPs) (Christoff et al., 2011; Blanke, 2012; Seth, 2013). SRP processes, also known as “extended” (Damasio, 1999) or “narrative” (Gallagher, 2000)–self processes, have so far received the bulk of the neuroimaging community’s attention and have been shown to be closely linked to the subjective content and neural activity attributed to the default-mode network (DMN, Raichle et al., 2001), in particular involving medial regions (Gusnard et al., 2001; Northoff et al., 2006; Buckner et al., 2008; Andrews-Hanna et al., 2010). These reference the “self-as-object” (James, 1890) and typically involve tasks assessing one’s personality, traits, name, or appearance. As such, they include higher-order cognitive functions such as evaluation, judgment, and reflective thought (Legrand and Ruby, 2009; Christoff et al., 2011; Northoff...
SSPs reference the “self-as-subject” (James, 1890). They implement a functional self/nonself distinction in perception, action, cognition, and emotion (Christoff et al., 2011). In line with this, self-specific features have been defined as being exclusive and non-contingent, meaning that they characterize oneself and no-one else, and that “changing” or “losing” them entail “changing” or “losing” the distinction between self and nonself. So far, neurocognitive attempts to investigate SSPs have employed paradigms which “changed” self-specific features, resulting in an altered sense of agency and body-ownership (Farrer and Frith, 2002; Tsakiris et al., 2008, 2010; Nahab et al., 2011; Chambon et al., 2014), or self-identification, location, and perspective (Arzy et al., 2006; Blanke and Metzinger, 2009; Blanke, 2012; Guterstam et al., 2015). These studies highlight the involvement of the temporo-parietal junction. However, no neuroimaging study to date has reported on the volitional reduction of self-specific features, or on the neural substrate underlying conscious experience devoid of the felt distinction between the “self” and “world.”

Other important but still unresolved questions include: are SSPs all-or-nothing or graded phenomena, and can attentional training drive SSP-neuroplasticity? Christoff et al. (2011) argue that addressing these questions necessitate broadening our understanding of the self-experience by incorporating subjective measures into neuroimaging protocols, as previously emphasized by Varela’s neurophenomenology research program (Varela et al., 1991; Varela, 1996). In particular, Varela suggested collaborating with highly skilled meditation practitioners as “…mindful awareness practices can provide a natural bridge between cognitive science and human experience (phenomenology). Particularly impressive to us is the convergence that we have discovered among the main themes concerning the self and the relation between subject and object.” (Varela et al., p. 33).

It should be noted that contemplation-induced loss of self is different from loss of self as evidenced in psychopathology. The former is basic to the sense of felt meaning and purpose in human existence, while the latter reflects the extremity of its collapse (Hunt, 2007). Buddhist notions of selflessness emphasize flexibility in the perception of the self, which leads to eudemonic happiness and optimal functioning (Dambro and Ricard, 2011). The meditation styles directly aimed at achieving such states are categorized under the “Deconstructive family” (Dahl et al., 2015). These target the implicit belief that the self is static, enduring and unitary, and replacing identification with it by identification with the phenomenon of experiencing itself (Dalai Lama, 1997).

The current article addresses these issues through a neurophenomenological exploration (Lutz et al., 2002; Thompson et al., 2005) of the sense-of-boundaries (SB), the fundamental division of the field of experience to a “self” versus a “world.” By collaborating with a uniquely qualified meditation practitioner (see section “Methods”), the SB experience was volitionally and repeatedly produced as a graded phenomenon, from a normal SB (SB1) to a state where the SB began to dissolve (SB2) and finally to a state where the SB disappeared (SB3), while brain activity was recorded using magnetoencephalogram (MEG). These states were investigated using a first-person approach where in-depth phenomenological interviews were conducted, and the collected data were analyzed using the grounded approach (explained in great detail in Ataria et al., 2015). The phenomenological interview method elicits from interviewees their own descriptions in their own words, “bracketing out” predetermined descriptive categories and concepts (such as Buddhist jargon).

In addition, the grounded theory approach considers data with no hypotheses or categories fixed at the outset, staying as close as possible to the data. Through this process, nine categories of experience that diminished during the shifts between the three SB stages were identified. These are presented and discussed in detail in Ataria et al. (2015). The categories are summarized in Table 1 below. The main conclusions of the phenomenological inquiry were that the SB should be defined in terms of flexibility, rather than location; and that the more flexible the SB, the weaker these phenomenal categories become, some dissolving completely and some maintaining a very weak presence.

The phenomenal categories outlined above map onto theoretical and experimental conceptualizations which have been previously explored by phenomenologists and cognitive neuroscientists. Specifically, we are referring to self-awareness, including its extended/narrative and core/minimal aspects (using Damasio, 2010 and Gallagher, 2000 terminology, respectively). The categories of “time,” “location” and “self” map onto the self-as-object extended self-conceptualization (Damasio, 2010), whereas the core/minimal self-concept has been argued to be composed of the categories of “internal-external,” (Christoff et al., 2011) “agency,” and “ownership” (Gallagher, 2000) and “center” (Zahavi, 2006). The status of the “TTS” and “bodily feelings” categories is less clear (Gallagher, 2000, 2013). Though possibly related to the minimal self-concept, they are better understood in terms of Damasio’s (2010) proto-self-concept, conceptualized as primordial feelings of the living body (such as proprioception and kinesthesia), which precede the subjective experience of being a self. The suggested pre-minimal-self-status of the “TTS” and “bodily feelings” agrees with the phenomenal results that these two categories remain, to some degree, even when the SB (as defined by seven of its categories) disappears. The close link between the nine phenomenal categories and the narrative/minimal/selfless modes of awareness are further clarified in the Supplementary Material (Section 1.1, Supplementary Fig. S1). As a final point, it is important to keep in mind that the different modes of self-awareness are not mutually exclusive. While not self-specific, SRP (such as the narrative mode) do include also SSPs. Like other conscious mental content produced by the brain, SRP content expressed as thoughts and feelings is stamped with the subjective signature of being our thoughts and feelings. Thus, an encapsulated working model of self-awareness modes has been suggested (Gallagher, 2000; Damasio, 2010; Dor-Ziderman et al., 2013) and is adopted here.

These phenomenological insights were “front-loaded” (Gallagher and Sørensen, 2006) onto the experiment’s design and analysis in two ways. First, the gradually descending states of SB guided us toward performing a regression analysis, and thus examining not just differences between two brain states, but differences specifically related to the gradual process of SB dissolution. We thus searched for spatial and oscillatory, sensor and source-level signals which increased or decreased their activity together with the three different SB stages. Second, the close phenomenological link between the experience of SB and self-awareness mode allowed testing the neural results on an independent, previously recorded MEG dataset of proficient contemplative practitioners (reported in Dor-Ziderman et al., 2013), who produced in the MEG states of gradually descending self-awareness from an extended narrative sense of self to a minimal sense of self focused on the “here and now,” and finally to a selfless mode of awareness where the sense of ownership disappeared (see section “Methods” for more details). We hypothesized that: (i) The decrease in the SB would correlate...
with identifiable oscillatory systems in the brain (Stage 1), and that (ii) these would generalize to the meditator group’s data (Stage 2). We used MEG as the study’s research tool as it allows noninvasive but reliable source estimation of fast neural oscillatory rhythms (Hansen et al., 2010).

**Methods**

**Stage 1**

**Participant**

We collaborated with S (third author of this article), a male aged 64, who has been practicing mindfulness according to the Satipathana and Theravada Vipassana traditions for about 40 years, with over 20,000 accumulated hours. S was chosen for the present study for two reasons: (i) His proven skill (based on five previous phenomenological interviews) in producing on-demand unique states of consciousness, sustaining them, describing them in rich detail as they unfold, carrying out reflexive processes without “interfering” with the first-person pre-reflexive experience, and precisely defining the limitations of his descriptions; (ii) His ability to accomplish these feats under experimental conditions. Laboratory settings introduce a set of nontrivial constraints and pressures which can make it difficult even for experienced practitioners to perform as well as they would under optimal conditions. Over the past 10 years, S has been collaborating with neuroscientists in neuroimaging studies using a variety of methodologies including

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**Table 1. The nine phenomenal categories and their expression during the SB stages**

| Category                | Brief explanation                                                                 | Degree during different stages |
|-------------------------|-----------------------------------------------------------------------------------|--------------------------------|
| Internal vs. external   | As the SB becomes more flexible, it is much less clear what is “inside” and what is “outside”; the experience of in versus out fades away. From the perspective of the SB, the concept of in versus out can be defined in terms of “priority.” There is no strict line between inside and outside, instead there is a continuum: something more important is “closer” and as things become less important, they grow increasingly distant. | SB1  | SB2  | SB3  |
| Time                    | The sense of time weakens as SB becomes more flexible, in the third stage, it eventually disappears. Specifically, we are referring to a sense of past continuing into the future; to the reduction in the sense of duration; and finally, to the sense of continuity itself which also disintegrates. It seems that the sense of time is a “mirror reflection” of the SB. Thus, any alteration in the level of flexibility is reflected by an adjustment in the sense of time. | SB1  | SB2  | SB3  |
| Location                | As the SB becomes more flexible, one’s ability to locate oneself in space deteriorates. The sense of location is always relative to objects in space. When the SB becomes more flexible, the intentional structure weakens and, in turn, objects become less distinguishable. The ability to locate oneself dwindles gradually: at first (SB2) the ability to differentiate between left/right and up/down decreases and, subsequently (SB3), the sense of orientation in space is lost altogether. | SB1  | SB2  | SB3  |
| Self                    | As the SB becomes more flexible, the sense of self dissolves, thus becoming weaker. This process begins by expanding the sense of self (SB2) and, thereafter (SB3), as the SB disappears the sense of self disappears altogether. | SB1  | SB2  | SB3  |
| Agency                  | With an increase in the flexibility of the SB, the need for control declines. While in the SB2 the potential to act still exists, hence some sense of agency remains, in SB3 it disappears completely. | SB1  | SB2  | SB3  |
| Ownership               | As the SB becomes increasingly flexible, the sense of ownership (SO) becomes weaker. In the second stage a very thin SO remains, while in the third stage the SO disappears completely. | SB1  | SB2  | SB3  |
| Center                  | First-person-egocentric-bodily perspective. As the flexibility of the SB increases, the sense of being at the center (with one’s body as a reference point) decreases until eventually, in SB3, the body ceases to act as a reference point in relation to the outside world | SB1  | SB2  | SB3  |
| Touching-touched structure (TTS) | When touching an object, the boundary between subject and object is at its clearest. Essentially, the TTS stands at the core of the intentional structure. As the SB becomes increasingly flexible, the TTS weakens, yet “it does not disappear altogether.” One can undergo a very fluid touching/being-touched kind of experience without generating a SB. This notion is comprehensible when the TTS is described on the level of the entire body touching (and being touched) by the world. | SB1  | SB2  | SB3  |
| Bodily feelings         | As the SB becomes increasingly flexible, bodily feelings, including proprioception and kinesthesia, become weaker. Yet even when the SB disappears, a minimal level of dynamic proprioception continues to exist: there remains a sense that there is a body without any experience of an SB | SB1  | SB2  | SB3  |

Key: strong; medium; weak; nonexistent.
electroencephalogram (EEG) (Berkovich-Ohana et al., 2012, 2014), MEG (Berkovich-Ohana et al., 2013; Dor-Ziderman et al., 2013), and fMRI (Berkovich-Ohana et al., 2016). Regarding S’s involvement in the study, S’s role in the study was that of a unique subject who generously contributed his time, effort, and unique expertise to the practice, production, and description of the SB states in a manner conducive to neurophenomenological research. He was not involved in the formulation of hypotheses, analysis of the data (phenomenological and neurophysiological), or in the interpretation of the results.

Procedure
Immediately after accepting S’s approval, a series of meetings were set up in which the proposed study was introduced, the optimal number of SB states determined, and it was verified that S could produce on demand states corresponding to different levels of SB which were (i) replicable, (ii) differentiated enough, and yet (iii) true to the complexity of the experience, and finally, (iv) open to a high level of description. A phenomenological interview (following the methods described in Petitmengin, 2006 and Vermersch, 2009) took place in the MEG laboratory while lying supine within the scanner with closed eyes—in conditions similar to the subsequent brain recording session. S described his inner experience after meditating as selfless mode. All epochs were initiated by an auditory cue.

MEG data acquisition
MEG recordings were conducted with a whole-head, 248-channel magnetometer array (4D Neuroimaging, Magnes 3600 WH) in a magnetically-shielded room. Reference coils located approximately 30 cm above the head oriented by the x, y, and z axes were used to remove environmental noise. Head position was indicated by attaching 5 coils to the scalp and determining, to a 1 mm resolution, their position relative to the sensor array before and after measurement. Discrepancies of less than 5 mm were measured in each of the five coils. Head shape and coil position were digitized using a Polhemus FASTTRAK digitizer. Brain signals were recorded with a sample rate of 1017.25 Hz and an analog online 0.1–400 Hz band-pass filter. The instructions for each condition were presented using E-prime 2.0 and delivered via a STAX SRS-005 amplifier and SR-003 push-pull electrostatic earpieces coupled with a vinyl tube to silicon earpieces to prevent magnetic noise within the shielded room.

Cleaning and preprocessing
Data processing and analysis was performed using Matlab®2009b and FieldTrip toolbox for MEG analysis (Open Source Software for Advanced Analysis of MEG, Oostenveld et al., 2011). Data were cleaned for line frequency (by recording on an additional channel the 50 Hz from the power outlet, and subtracting the average power-line response from every MEG sensor), building vibration (measured in x, y, and z directions using three Bruel and Kjaer accelerometers), and heartbeat artifacts using the methods described in Tal and Abeles (2013). One malfunctioning MEG sensor was identified and its data were removed from further analysis. The data were segmented into nonoverlapping 2-s epochs, which were visually examined for muscle and jump (in the MEG sensors) artifacts. Contaminated epochs were removed from further analysis. To ensure the removal of all heartbeat, eye, and muscle artifact, an independent component analysis (ICA) was performed on the data (Jung et al., 2000). Segmented data were down-sampled to 300 Hz to speed up data decomposition. The data were then decomposed into a set of independent components (247, as the number of remaining sensors) ordered by degree of their explained variance. Components indicating heartbeats or eye movements were determined by visual inspection of the 2D scalp maps and time course of each component. Two components were taken out, and the resultant unmixing matrix was used to compute the time-courses of the data in its original high-temporal resolution.

Sensor space analysis
A whole-head frequency analysis for low (2–40 Hz) and high (40–90 Hz) frequencies at 1 Hz resolution was performed. For each 2-s epoch in each sensor, a Fast Fourier Transform (FFT) with a Hanning taper was applied to overlapping fixed-length sliding time windows (every 50 ms), which were then averaged, yielding one value per sensor, epoch, and frequency.

![Figure 1. Experimental setup for Stage 1 (top) and Stage 2 (bottom). SB, sense of boundaries; NS, narrative self-mode; MS, minimal self-mode; SL, selfless mode. All epochs were initiated by an auditory cue.](image-url)
windows of different lengths as well as different degrees of smoothing were used for low and high frequencies: 0.5 s and 2 Hz smoothing for 2–40 Hz, and 0.2 s and 14 Hz smoothing for 40–90 Hz (Gross et al., 2013).

For determining frequency-specific neural activity related to the gradual decrease in the sense of boundaries (SB), the epochs were grouped into the three conditions outlined previously (SB1, SB2, SB3) and subjected to a regression analysis, yielding a regression coefficient t-statistic. This procedure was performed independently (over sensors/frequencies) in two stages (see smoothing for 40–90 Hz (Gross, 2005 s and 2 Hz smoothing for 2–40 Hz, and 0.2 s and 14 Hz spectral smoothing were used for low and high frequencies: windows of different lengths as well as different degrees of smoothing were used for low and high frequencies: 0.5 s and 2 Hz smoothing for 2–40 Hz, and 0.2 s and 14 Hz smoothing for 40–90 Hz (Gross et al., 2013).)

Stage 2
Setup
The participant group consisted of 12 right-handed long-term mindfulness meditators (9 males and 3 females, mean age 45.2, averaging over 16 years and 11 000 h of formal practice). This group included S as it was part of a larger experiment containing tasks unrelated to the ones reported here (some of them reported in Berkovich-Ohana et al., 2013; Dor-Ziderman et al., 2013). S’s data, however, was not analyzed to avoid confirmation circularity. Here we used the latter dataset but implemented a novel analysis procedure, matching the current study’s aims. The purpose of the previous study (Dor-Ziderman et al., 2013) was to outline the differential spatial and spectral mechanisms mediating narrative versus minimal modes of self-awareness. The current analysis set out to partially validate Stage 1 results on an independent group of meditators by determining whether the hypothesized brain mechanisms (regions and frequency bands) were indeed correlated with the subjective attenuation of self-awareness.

As part of the experimental procedure, the participants were requested via aural prerecorded instructions to produce, voluntarily, three modes of awareness for 30 s, three times for each state with their eyes closed (see Fig. 1). The first mode was “narrative” (operationalized as “try to think what characterizes you”), defined as a mode of self-awareness weaving episodic memory, future planning, and self-evaluation together with a coherent self-narrative and identity; the second was “minimal” (operationalized as “Try to experience what is happening to you at the present moment”), a minimal mode of self-awareness focused on present momentary experience and closely tied to the sense of agency and ownership (Gallagher, 2000); and the third was “selfless” (operationalized as “Try to experience what is happening at the present moment, when you are not in the center”), a mode of awareness defined by and practiced within Buddhist contemplative traditions, in which identification with a static self is replaced by identification with the phenomenon of experiencing itself (Dalai Lama, 1997). As this mode of awareness may be alien to readers unfamiliar with meditation experience, we supply below two of the meditators’ experience reports: sub12: “It was emptiness, as if the self fell out of the picture. There was an experience but it had no address, it was not attached to a center or subject. It was not 100%, but there was no sense of an object there running the show.”; and sub14: “It was to be aware of the body, the sensations, pulse, location of limbs, sounds and sights—to be only a witness to all this.”

Throughout the successive volitional shift of the sense of self between the three modes, MEG was recorded. Online as well post-experiment retrospective data were collected including measures of task success and stability. The online measure was a 1–3 (3 meaning no success) rating of task performance success after each 30-s epoch (triggered by a bell sound with 3 indicating no success). No scores of 3 were recorded. The retrospective measures were collected outside the MEG after the
experiment. The scores were high: an average of 8.13 and 7.93 (on a 1–10 scale) for success and stability, and were not significantly different across the narrative, minimal, and selfless conditions (for further details, see Dor-Ziderman et al., 2013). Regarding first-person data, as talking during MEG recording may cause movement artifacts, the collected phenomenological descriptions were limited to the selfless state which was the last state produced (see Fig. 1). Immediately after participants produced this state, the MEG recording stopped and first-person descriptions were collected.

Analysis and statistics
The details regarding MEG data collection, cleaning, and pre-processing are similar to what has been described in Stage 1. The data of one subject could not be analyzed due to a volume alignment problem. The data of the remaining 10 subjects were analyzed in two stages: First, we checked whether significant regression values were present for the delta (1–4 Hz), theta (5–7 Hz), alpha (8–13 Hz), beta (14–30 Hz), low gamma (31–50 Hz), and high gamma (51–90 Hz) frequency bands. This was done by averaging over all sensors for each subject and then conducting a one-sample t-test of the pooled group results against the null hypothesis that the distribution would have a zero mean. We hypothesized that significant frequency band/s would match those found in Stage 1. In order to control for carry over effects possibly resulting from the lack of counterbalancing or randomization of the trial/block type, the same analysis was performed on two other conditions (related to the sense of “time” and “space”) which were identical in design (three states, each state produced for 3 x 30 s, see Supplementary Fig. S4 for more detail). We hypothesized that here the significant frequency band/s would not match those found in Stage 1.

In the second stage, source localization was carried out in a similar manner to the one described in Stage 1. For facilitating a group analysis, all brain volumes were aligned to the same template brain detailed in the “Methods” section, thus creating a common anatomical space on which group statistics could be performed. Source estimation was computed on the peak frequency within the determined frequency band of interest from the Stage 2 group data. In addition, a one sample t-test of the Stage 2 group results against subject S’s results from Stage 1 was conducted in order to highlight differences in terms of the effects’ spatial overlap extent. Given that subject S is such a highly-skilled practitioner, we hypothesized that the effects found for S would also be more pronounced relative to the other meditators. Statistics were assessed using a cluster-based non-parametric permutation approach on pooled regression t-values (Maris and Oostenveld, 2007).

Results
Stage 1
Sensor space
Averaging overall channels, the regression analysis indicated significant negative regression coefficient values in the beta band (marked by red circles), peaking at 27 Hz (Fig. 2a). No positive regression values were found in any of the frequency bands. In addition, regrouping of the conditions by order of presentation did not change the reported findings (see Supplementary Fig. 3), thus partially controlling for the fixed order of SB states production and ruling out the possibility that the results could be explained by their temporal ordering alone. In addition, the baselining of the data using the 1-min rest period in each block did not change the results meaningfully (see Supplementary Fig. 4), suggesting the results reflect decreases in beta band power (rather than a return to equilibrium).

The significant frequencies (22–33 Hz) were defined as FOI, interpreted as a beta band effect. While frequencies greater than 30 Hz are often interpreted as indicating the gamma band, the present data set suggests a beta band label to be more adequate. As can be seen in Fig. 2a, immediately after the 27 Hz peak, there is a sharp decrease in regression significance which continues and is maintained throughout the gamma band. In addition, significant peaks are present also in lower beta frequencies (16–18 Hz). These suggest that the spill into the higher frequencies reflects spectral leakage. Finally, the Stage 2 results (see section “Sensor space”), defined using a standard band definition (14–30 Hz), implicate the beta band (and only the beta band), further strengthening beta band interpretation of the results.

Subsequently, the effect’s spatial topography was examined. The spatial topography driving the beta band effect is presented in Fig. 2c and d, with significant sensors marked with bold stars. As can be seen the effect is pronounced over bilateral frontal and central sites. Fig. 2c shows the respective decrease in beta power percent in signal change (PSC) over these sensors; and Fig. 2d shows the overall statistical regression map. The mean power values over significant bands and sensors were averaged and subjected to a post hoc analysis (Fig. 2b).

Source space
The sources of the significant beta band regression for subject S are presented in Fig. 3, and further anatomical detail of the images is supplied in Table 2. In line with the sensor space data, only negative regression values were found. The results indicate a large widespread cluster of voxels manifesting over lateral (top images) and medial (bottom images) parietal regions, more extensively in the right hemisphere (right images). On the lateral surface of both hemispheres, the regions comprising the TPJ, namely, the inferior parietal lobule (IPL), supramarginal gyrus (SMG), angular gyrus (AG), superior temporal gyrus (STG), and middle temporal gyrus (MTG) are the main loci of the regression effect. In addition, the effect extends to primary sensory and motor regions and insular regions. On the medial surface, the precuneus (PrC) and middle/posterior cingulate gyrus bilaterally (M/PCC), as well as the supplementary motor area (SMA) in the right hemisphere also evidenced significant regression values.

Stage 2
Sensor space
The regression analyses over all sensors for the delta, theta, alpha, beta, low and high gamma bands yielded significant negative regression coefficient values in the beta band alone \(T(1, 9) = -3.91, P < 0.0036 \) (0.018 after Bonferroni correction), with the peak frequency at 21 Hz. The other frequency bands did not exhibit significant values (even before the Bonferroni correction). In addition, the regression analyses of the control “time” and “space” blocks in the beta band did not yield significant results, suggesting that the reported beta band effect could not be attributed to the fixed order of the blocks.

Source space
The sources of the significant beta band regression for the group-level analysis \(n = 10\), masked by S’s ROI’s, are presented
Figure 2. Sensor-level results. Determining FOI: (a) Frequencies (x-axis) regression t-values (y-axis) plot, averaged overall sensors. Red circles indicate statistically significant t-values ($P < 0.0005$, FDR corrected); Statistical bar plot: (b) Mean power (y axis) and standard error bars averaged over FOI (22–33 Hz) and SOI for SB1, SB2, and SB3; Raw effect: (c) of percent-in-signal-change (psc) between SB1 and SB2 (left) and SB2 and SB3 (right). Color bar indicates psc from 0.2 (dark red) to –0.2 (dark blue); Determining SOI: (d) 2D regression t-map averaged over the FOI (22–33 Hz). Dots on the map represent sensors; stars signify significant sensors ($P < 0.0005$, Monte Carlo permutation corrected). Color bar scale indicates t-values from 0.6 (dark red) to –0.6 (dark blue).* $P < 0.0335$; ** $P < 1.07 \times 10^{-7}$ (both Bonferroni corrected).

Figure 3. Beamforming beta band source estimation statistical images for subject S. Lateral (A1 and B1) and medial (A2 and B2), left (A1 and A2) and right (B1 and B2), views of S’s source estimates overlaid on SUMA 3D cortical surface model. Color bar indicates t-value degree from 6 (dark red) indicating a positive linear pattern to –6 (dark blue) indicating a negative linear pattern. Images significant at $P < 0.0005$ (Monte Carlo Permutation corrected). Lateral views (top) highlight the TPJ regions in both hemispheres; while the medial views (bottom) highlights the Prc and M/PCC gyrus bilaterally, and the SMA in the right hemisphere. For more detailed anatomical information, refer to Table 2.
in Fig. 4, and further anatomical details of the images are supplied in Table 3. Again, only negative regression coefficients were found. The findings indicate a large right hemisphere cluster peaking in the AG. The majority of the cluster is comprised of right TPJ regions (IPL, SMG, AG and STG; B1 in Fig. 4), with weaker and smaller extensions to the pre- and postcentral gyrus, and the insula and inferior frontal gyrus. On the medial surface, the cingulate cortex (M/PCC) and the precuneus (PrC) also evidenced significant regression values (B2 in Fig. 4), though much smaller than those in S’s data.

Table 2. Beamforming beta band source estimation info for subject S (n = 1)

| Brain regions (Talairach–Tournoux atlas) | Overlap (%) | Left | Right |
|-----------------------------------------|-------------|------|-------|
| Inferior Parietal lobule                 | 5.4         | 6.1  |
| Postcentral gyrus                       | 5.5         | 5.8  |
| Precentral gyrus                        | 5.6         | 5.5  |
| Cingulate gyrus                         | 3.0         | 3.9  |
| Superior Temporal gyrus                 | 3.6         | 2.4  |
| Insula                                  | 1.4         | 1.9  |
| Supramarginal gyrus                     | 1.8         | 1.8  |
| Medial Frontal gyrus (SMA)              | —           | 1.6  |
| Parscentral lobule                      | 0.4         | 1.3  |
| Middle Temporal gyrus                   | 1.1         |      |
| Middle Frontal gyrus                    | 0.5         | 1.1  |
| Precuneus                               | 1.0         | 1.0  |
| Inferior Frontal gyrus                  | 0.4         | 0.9  |
| Angular Gyrus                           | —           | 0.8  |

Image threshold: $p < 0.0005$ (Monte Carlo permutation corrected)

Information supplied includes total number of voxels, hemispheric overlap, peak voxel characteristics, image statistical threshold, brain regions involved, and their overlap with the significant voxels. The AFNI supplied TT Daemon atlas was used. Due to poor resolution and signal leakage to non-brain regions, overlap percentages do not add up to 100%.

Supplementary Fig. S5 (in Supplementary Section 3.1) presents the source images of the one-sample t-test between S and the meditators’ group (n = 10) regression coefficients. These largely overlap with S’s results, in line with S being a uniquely skilled practitioner. In addition, Supplementary Fig. S5 presents the unmasked (by S’s ROI) group results. These reveal additional occipital and right frontal lateral regions which evidence significant beta band regression effects, interpreted as indicating increased attentional resource allocation for producing the deeper meditative SB states (Saggar et al., 2012; see...
Table 3. Beamforming beta band source estimation info for meditators group (n = 10)

| Brain regions (Talairach–Tournoux atlas) | Overlap (%) |
|----------------------------------------|-------------|
| Inferior parietal lobule               | ______      |
| Postcentral gyrus                      | ______      |
| Precentral gyrus                       | ______      |
| Supramarginal gyrus                    | ______      |
| Superior temporal gyrus                | ______      |
| Cingulate gyrus                        | ______      |
| Angular gyrus                          | ______      |
| Superior parietal lobule               | ______      |
| Insula                                 | ______      |
| Inferior frontal gyrus                 | ______      |
| Precuneus                              | ______      |

Image threshold: P<0.0005 (Monte Carlo permutation corrected)

Information supplied includes total number of voxels, hemispheric overlap, peak voxel characteristics, image statistical threshold, brain regions involved, and their overlap with the significant voxels. The AFNI supplied TT Daemon atlas was used. Due to poor resolution and signal leakage to non-brain regions, overlap percentages do not add up to 100%.

Supplementary Material, Section 3.1 for a more detailed discussion.

Discussion

The current study is the first to directly and ecologically tap SSPs, allowing uniquely-trained abilities and phenomenology to guide neuroscientific design and analysis. Together with our previous publication (Ataria et al., 2015), we demonstrate the graded rather than all-or-nothing nature of SSPs on both the experiential and neural levels. Our current results highlight two important findings regarding the neural mechanisms of SSPs. First, we demonstrated that beta oscillations are part of the neural processes associated with changes in the SB. Second, we showed that these modulations can be localized to mainly two anatomical regions in the lateral and medial parietal brain.

The TPJ region was the largest and most pronounced. The TPJ has been shown to play a significant role in self-related paradigms such as self-location (Ionta et al., 2011; Lenggenhager et al., 2011; Blanke, 2012; Guterstam et al., 2015), self-awareness as part of the default mode network (Northoff et al., 2006; Buckner et al., 2008), agency and ownership (Farrer and Frith, 2002; Farrer et al., 2003, 2008; Tsakiris et al., 2010; Dor-Ziderman et al., 2013; Kühn, et al., 2013; Chambon et al., 2014; Khalighinejad and Haggard, 2015), egocentric perspective (Creem et al., 2001; Wraga et al., 2005; Easton et al, 2009) and first-person perspective taking (Ruby and Decety, 2001; Vogeley et al., 2004; Ionta et al., 2011). In addition, the literature on out-of-body experiences (OBE), where the unity of self and body is disrupted, and in particular studies where such experiences are produced using full-body illusions (Blanke and Metzinger, 2009), have been linked to the constructs of self-location, agency and ownership, egocentric/first-person perspective, as well as to the TPJ (Blanke et al., 2002; Blanke, 2005a, 2005b; Arzy et al., 2006; Ridder et al., 2007). The right lateralization of the results is aligned with the literature, as lesions leading to OBEs are usually to be found in right parietal regions (Ionta et al., 2011). In addition, studies of multisensory integration of bodily self-awareness (Blanke, 2005b; Arzy et al., 2006; Ionta et al, 2014), and the sense of agency (Ruby and Decety, 2001; Farrer et al., 2003; Decety and Lamm, 2007), report effects either more pronounced, or limited to, the right hemisphere.

On the medial surface, the highlighted MPC region is a well-established region mediating self-awareness, reaching back to the original studies of the default mode network (Raichle et al., 2001), and supported by large-scale quantitative meta-analyses of brain imaging studies on self-processing (Northoff et al., 2006; Buckner et al., 2008; Schneider et al., 2008; Kim, 2012). Within the self-network, while the medial prefrontal regions were shown to be involved in self-evaluation (Kwan et al., 2007; Luber et al., 2012), the medial parietal region has been suggested to code for the integration of self-referential stimuli within the context of one’s own person (Lou et al., 2004; Northoff and Bermpohl, 2004), and for the experience of self-identification (Brewer et al., 2013; Garrison et al., 2013; Josipovic, 2013). In addition, the MPC was found to play a major role in studies directly relevant to minimal self-processing, but coming from diverse directions, including fMRI neuroimaging (Araujo et al., 2015), neurophenomenology (Dor-Ziderman et al., 2013), minimally-conscious patients (Laureys et al., 2004), lesion patient studies (Philippi et al., 2012), as well as brain synchrony (Lou et al., 2010).

We interpret these findings as indicative of two concurrent neurofunctional processes which give rise to the experience of diminished SB. The first is freeing conscious awareness from its habitual identification with a self via suppression of the integrative aspect of the self-network in the MPC. The second is a disruption of the self-body unity allowing awareness a measure of flexibility regarding its habitually perceived egocentric location and perspective. Enacting only the former process may result in an OBE type of experience where a spatial shift in the sense of self is induced (Ionta et al., 2011; Blanke, 2012). However, in such cases, the sense of there being a self versus world does not change, only the boundaries are remapped. In other words, the brain maintains its habitual tendency of enacting SSPs and separating the field of experience into self/nonself.

The current setup does not allow inferring causality; however, there is evidence that the MPC can be trained to decrease its activity, as reported in long-term meditators (Brefczynski-Lewis et al., 2007; Brewer et al., 2011; Taylor et al., 2011; Pagnoni, 2012; Berkovich-Ohana et al., 2013; Dor-Ziderman et al., 2013; Marzetti et al., 2014). This suggests that the volitional attenuation of the MPC is a mechanistic target of mindfulness meditation (Brewer and Garrison, 2014). Relying on phenomenological and fMRI data, Josipovic (2013) suggested that the MPC is significantly involved in modulating the fragmentation of experience...
into subjective versus objective, or self versus other, in meditators. Neurophysiological results tie such states, though not exclusively, to beta band cortical desynchronization (Lehmann et al., 2012; Sagar et al., 2012; Dor-Ziderman et al., 2013; Muthukumaraswamy et al., 2013; Hinterberger et al., 2014; Hauswald et al., 2015).

The current results indicate that the beta band is associated with modulating SSPs. It has been suggested, based on converging evidence from studies of the motor system and related pathophysiology as well as top-down mechanisms involved in cognitive and perceptual processing, that beta band activity (BBA) is related to the maintenance of the current motor/cognitive set. Thus, enhanced BBA signals the intention or prediction of maintaining the status quo while suppression of BBA is argued to signal the opposite—the intention and prediction for disruption of the status quo (Engel and Fries, 2010). Applying this hypothesis to the current study, one’s normal, default SSPs gives rise to a natural and powerful subjective state of SB that is rarely perturbed. The SB stems from early constantly adapting evolutionary needs (Llinás, 2001; Damasio, 2010), and as such, involves primitive neural mappings which can be argued to constitute the lowest level of subjective experience and indeed consciousness (Damasio and Carvalho, 2013). Consequently, volitionally manipulating this powerfully implanted SB and producing attenuated and even null states of SB would constitute a gross disruption of the habitual cognitive-experiential status quo, and would thus, necessitate a marked reduction in BBA.

The graded nature of SSPs and its trainability leading to the loss of the distinction between “self” and “world” point to a self which is constructed and continuously remade by particular and transient neural processes. That the self is a unitary entity only in the phenomenal sense is an idea which is not alien to the neurocognitive literature. It has been discussed already by William James in the chapter “Consciousness of Self” in his “Principles of Psychology” (James, 1890), and is the topic of numerous current books authored by influential neuroscientists, psychologists, and philosophers (e.g., Llinás, 2001; Metzinger, 2004; Damasio, 2010; Hood, 2012; Harris, 2014). This view of transient selfhood is aligned with the view held by Eastern meditative traditions (see Gani, 2012; Thompson, 2015 for an in-depth discussion), and Buddhist ones in particular, which have long claimed that the self is entirely a constructed habit, a transient selfhood is aligned with the view held by Eastern meditative traditions (see Ganeri, 2012; Thompson, 2015 for an in-depth discussion), and Buddhist ones in particular, which have long claimed that the self is entirely a constructed habit, a

The distinct neural characterization and plasticity of SSPs may hold practical value for clinical populations suffering from abnormal SB. For example, during trauma, an involuntary shift from the regular daily experience to a sense of rigid and closed SB may be enacted as a defense mechanism (Ataria, 2013, 2014). In addition, depersonalization disorder (DPD) is characterized by a sense of unreality about the self and the world, and thus directly reflects a disturbed mode of SSP (Sierra and David, 2011). Gray matter changes in the frontal, temporal, and parietal lobes (both lateral and medial) are associated with DPD (Sierra et al., 2014), as well as hyperactivation of the TPJ (Simeon et al., 2000). Finally, preliminary studies suggest that noninvasive stimulation of the right TPJ may be a therapeutic option for DPD. Repetitive transcranial magnetic stimulation over the course of weeks in DPD patients resulted in an impressive reduction of symptoms in about half of the patients (Mantovani et al., 2011). The present study’s novel contribution in highlighting the associated frequency band and electrodes’ spatial location may further aid clinicians both in early detection of SSPs’ abnormalities, as well as the design of neurofeedback interventions (Bagdasaryan and Quyen, 2013), in particular, interventions utilizing immersive virtual reality environments which allow ecologically relevant learning (Gruzelier et al., 2010).

The current study suffers from a number of drawbacks. The first is the study’s design which lacked randomization in the ordering of conditions. Attempts were made to control for this flaw (see section “Methods,” “Sensor space analysis,” and “Analysis and statistics”; and Supplementary Material Sections 2.1 and 2.2), which was largely due to the neurophenomenological nature of the study which imposed certain restrictions both in terms of facilitating the production of these rare states, as well as the requirements of phenomenological data collection. As the concepts and processes engaged with are difficult to operationalize, and similar studies are scarce, refining methodology is a task for future experimentation. A further drawback is that the prior neural hypothesis is based on a single subject. While this drawback was partly overcome by corroborating the results in a larger group, the degree to which the results can be generalized to wider, non-meditative populations is uncertain. As such, the study is preliminary. In addition, the study’s setup does not support inferring causality (that the modulation of beta oscillations causes changes in the SB). We cannot completely rule out the possibility that the reported changes may be due to downstream effects of other processes, or could be purely epiphenomenal. Nevertheless, despite these limitations, this proof-of-concept study illustrates that studying subtle but profound aspects of self-identity is tenable by incorporating first-person data into neuroimaging experimental protocols. We hope it will spark further robust examination of the brain mechanisms, trainability, and clinical applicability of SSPs.

Supplementary Data

Supplementary data is available at Neuroscience of Consciousness Journal online.

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Conflict of interest statement. None declared.

References

Andersson-Stina J, Reiderm JS, Sepulcre J et al. Functional-anatomic fractionation of the brain's default network. Neuron 2010;65:550–62.

Araujo HF, Kaplan J, Damasio H et al. Neural correlates of different self domains. Brain Behav 2015;5:e00409.

Arzy S, Thut G, Mohr C et al. Neural basis of embodiment: distinct contributions of temporoparietal junction and extrastriate body area. J Neurosci 2006;26:8074–81.

Ataria Y. Sense of ownership and sense of agency during trauma. Phenomenol Cogn Sci 2013;14:199–212.

Ataria Y. Dissociation during trauma: the ownership-agency tradeoff model. Phenomenol Cogn Sci 2014;14:1037–1053.

Ataria Y, Dor-Ziderman Y, Berkovich-Ohana A. How does it feel to lack a sense of boundaries? A case study of a long-term mindfulness meditator. Conscious Cogn 2015;37:133–147.

Austin J. Selfless Insight: Zen and the Meditative Transformations of Consciousness. Cambridge, MA: MIT Press, 2009.

Bagdasaryan J, Quyen MLV. Experiencing your brain: neurofeedback as a new bridge between neuroscience and phenomenology. Front Hum Neurosci 2013;7:680.

Baird B, Smallwood J, Lutz A et al. The decoupled mind: mindwandering disrupts cortical phase-locking to perceptual events. J Cogn Neurosci 2014;26:1–12.

Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. J R Stat Soc Series B 1995;57:289–300.

Berkovich-Ohana A, Dor-Ziderman Y, Glicksohn J et al. Alterations in the sense of time, space, and body in the mindfulness-trained brain: a neurophenomenologically-guided MEG study. Front Psychol 2013;4:912.

Berkovich-Ohana A, Glicksohn J, Goldstein A. Mindfulness-induced changes in gamma band activity - Implications for the default mode network, self-reference and attention. Clin Neurophys 2012;123:700–10. doi:10.1016/j.clinph.2011.07.048

Berkovich-Ohana A, Glicksohn J, Goldstein A. Studying the default mode and its mindfulness-induced changes using EEG functional connectivity. Soc Cogn Affect Neurosci 2014;99:1616–24.

Berkovich-Ohana A, Harel M, Hahamy A et al. Alterations in task-induced activity and resting-state fluctuations in visual and DMN areas revealed in long-term meditators. NeuroImage 2016;135:125–134.

Blanke O. Linking out-of-body experience and self processing to mental own-body imagery at the temporoparietal junction. J Neurosci 2005a;25:550–7.

Blanke O. The out-of-body experience: disturbed self-processing at the tempo-parietal junction. The Neuroscientist 2005b;11:16–24.

Blanke O. Multisensory brain mechanisms of bodily self-consciousness. Nat Rev Neurosci 2012;13:556–71.

Blanke O, Metzinger T. Full-body illusions and minimal phenomenal selfhood. Trends Cogn Sci 2009;13:7–13.

Blanke O, Ortigue S, Landis T et al. Stimulating illusory own-body perceptions. Nature 2002;419:269–70.

Brefczynski-Lewis JA, Lutz A, Schaefer HS et al. Neural correlates of attentional expertise in long-term meditation practitioners. Proc Natl Acad Sci USA 2007;104:11483–88.

Brewer JA, Garrison KA. The posterior cingulate cortex as a plausible mechanistic target of meditation: findings from neuroimaging. Ann N Y Acad Sci 2014;1307:19–27.

Brewer JA, Garrison KA, Whitfield-Gabrieli S. What about the “self” is processed in the posterior cingulate cortex?. Front Hum Neurosci 2013;7:647.

Brewer JA, Worhunsky PD, Gray JR et al. Meditation experience is associated with differences in default mode network activity and connectivity. Proc Natl Acad Sci U S A 2011;108:20254–20259.

Chambron V, Andrews-Hanna JR, Schaeter DL. The brain’s default network: anatomy, function, and relevance to disease. Ann N Y Acad Sci 2008;1124:1–38.

Chambron V, Moore JW, Haggard P. TMS stimulation over the inferior parietal cortex disrupts prospective sense of agency. Brain Struct Funct 2014;220:3627–3639.

Christoff K, Cosmelli D, Legrand D et al. Specifying the self for cognitive neuroscience. Trend Cogn Sci 2011;15:104–12.

Creem SH, Downs TH, Wraga M et al. An fMRI study of imagined self-rotation. Cogn Affect Behav Neurosci 2001;1:239–49.

Dahl C, Lutz A, Davidson RJ. Reconstructing and deconstructing the self: cognitive mechanisms in meditation practice. Trends Cogn Sci 2015;19:515–23.

Dalai Lama X, (1997). In: Varela FJ (ed.), Sleeping, Dreaming, and Dying: An Exploration of Consciousness with the Dalai Lama. Somerville, MA: Wisdom Publications.

Damasio A. Self Comes To Mind: Constructing the Conscious Brain. New York: Pantheon, 2010.

Damasio A, Carvalho GB. The nature of feelings: evolutionary and neurobiological origins. Nat Rev Neurosci 2013;14:143–52.

Damasio AR. The Feeling of What Happens: Body and Emotion in the Making of Consciousness. New York: Harcourt, 1999.

Dambrun M, Ricard M. Self-centeredness and selflessness: a theory of self-based psychological functioning and its consequences for happiness. Rev Gen Psychol 2011;15:138–57.

Decety J, Lamm C. The role of the right temporoparietal junction in social interaction: how low-level computational processes contribute to meta-cognition. The Neuroscientist 2007;13:580–93.

Dor-Ziderman Y, Berkovich-Ohana A, Glicksohn J et al. Mindfulness-induced selflessness: a MEG neurophenomenological study. Front Hum Neurosci 2013;7:582.

Dunne J. Toward an understanding of non-dual mindfulness. Contemporary Buddhism 2011;12:71–88.

Easton S, Blanke O, Mohr C. A putative implication for fronto-parietal connectivity in out-of-body experiences. Cortex 2009;45:216–27.

Ekman P, Davidson RJ, Ricard M et al. Buddhist and psychological perspectives on emotions and well-being. Curric Perspect 2005;14:59–63.

Engel AK, Fries P. Beta-band oscillations–signalling the status quo?. Curr Opin Neurobiol 2010;20:156–65.

Farrer C, Franck N, Georgieff N et al. Modulating the experience of agency: a positron emission tomography study. NeuroImage 2003;18:324–33.

Farrer C, Frey SH, Van Horn JD et al. The angular gyrus computes action awareness representations. Cereb Cortex 2008;18:254–61.

Farrer C, Frith CD. Experiencing oneself vs another person as being the cause of an action: the neural correlates of the experience of agency. NeuroImage 2002;15:596–603.

Gallagher S. Philosophical conceptions of the self: implications for cognitive science. Trends Cogn Sci 2000;4:14–21.

Gallagher S. A pattern theory of self. Front Hum Neurosci 2013;7:443. doi:10.3389/fnhum.2013.00443
Gallagher S, Brøstøl Sørensen J. Experimenting with phenomenology. Conscious Cogn 2006;15:119–34.

Ganeri J. The Self: Naturalism, Consciousness, and the First-Person Stance. Oxford: Oxford University Press, 2012.

Garrison KA, Santoyo JP, Davis JH et al. Effortless awareness: using real time neurofeedback to investigate correlates of posterior cingulate cortex activity in meditators’ self-report. Front Hum Neurosci 2013;7:440.

Gross J, Baillet S, Barnes GR et al. Good practice for conducting and reporting MEG research. Neuroimage 2013;65:349–63.

Gross J, Kujala J, Hamalainen M et al. Dynamic imaging of coherent sources: Studying neural interactions in the human brain. Proc Natl Acad Sci USA 2001;98:694–99.

Gruzelier J, Inoue A, Smart R et al. Acting performance and flow state enhanced with sensory-motor rhythm neurofeedback comparing ecologically valid immersive VR and training screen scenarios. Neurosci Lett 2010;480:112–16.

Gusnard D a, Akbudak E, Shulman GL et al. Posterior cingulate cortex and self-referential mental activity: relation to a default mode of brain function. Proc Natl Acad Sci USA 2001;98:4259–64.

Guterstam A, Bjo¨ rnsdotter M, Gentile G et al. Cerebral gamma oscillations and self-agency. Front Psychol 2014;5:99.

Hansen P, Kringlebach M, Salmelin R (eds). MEG: An Introduction. New York, NY: Oxford University Press, 2010.

Harris S. Waking Up: A Guide To Spirituality Without Religion. New York: Simon & Schuster, 2014.

Hauswald A, Gross J, Kujala J, Hamalainen M et al. Reduced functional connectivity between cortical sources in five meditation traditions detected with lagged coherence using EEG tomography. Neuroimage 2012;60:1574–86.

Holzel BK, Lazar SW, Gard T et al. Mindfulness and neural perspective. Curr Biol 2015;25:1416–25.

Hansen P, Kringlebach M, Salmelin R (eds). MEG: An Introduction to Methods. New York, NY: Oxford University Press, 2010.

Harris S. Waking Up: A Guide To Spirituality Without Religion. New York: Simon & Schuster, 2014.

Hansfeld A, Ubelacker T, Leske S et al. Magnetoencephalographic study of self-agency. Cereb Cortex 2015;25:1416–25.

Hansen P, Kringlebach M, Salmelin R (eds). MEG: An Introduction to Methods. New York, NY: Oxford University Press, 2010.

Harris S. Waking Up: A Guide To Spirituality Without Religion. New York: Simon & Schuster, 2014.

Hauswald A, Gross J, Kujala J, Hamalainen M et al. Reduced functional connectivity between cortical sources in five meditation traditions detected with lagged coherence using EEG tomography. Neuroimage 2012;60:1574–86.

Hengstenhager B, Halje P, Blanke O. Alpha band oscillations correlate with illusory self-location induced by virtual reality. Eur J Neurosci 2011;33:1935–43.

Hölzel V, Vidal JR, Seeck M et al. Reduced functional connectivity between cortical sources in five meditation traditions detected with lagged coherence using EEG tomography. Neuroimage 2012;60:1574–86.

Hinterberger T, Schmidt S, Kamei T et al. Decreased electro-physiological activity represents the conscious state of emptiness in meditation. Front Psychol 2014;5:99.

Holzel BK, Lazar SW, Gard T et al. Mindfulness and neural perspective. Curr Biol 2015;25:1416–25.

Hood BM. The Self Illusion: How the Social Brain Creates Identity. New York: Oxford University Press, 2012.

Hunt HT. Dark nights of the soul*: Phenomenology and neuro-cognition of spiritual suffering in mysticism and psychosis. Rev Gen Psychol 2007;11:209–34.

Ionta S, Heydrich L, Lenggenhager B et al. Multisensory mechanisms in temporoparietal cortex support self-location and first-person perspective. Neurosci Lett 2011;491:363–74.

Ionta S, Martuzzi R, Salomon R et al. The brain network reflecting bodily self-consciousness: a functional connectivity study. Soc Cogn Affect Neurosci 2014;9:1904–13.

James W. The Principles of Psychology. New York, NY: Henry Holt and Company, 1890.

Josipovic Z. Neural correlates of nondual awareness in meditation. Ann N Y Acad Sci 2014;1307:9–18.

Josipovic Z, Dinstein I, Weber J et al. Influence of meditation on anti-correlated networks in the brain. Front Hum Neurosci 2011;5:183.

Jung TP, Makeig S, Westerfield M et al. Removal of eye activity artifacts from visual event-related potentials in normal and clinical subjects. Clin Neurophysiol 2000;111:1745–58.

Khaliqinejad N, Haggard P. Modulating human sense of agency with non-invasive brain stimulation. Cortex 2015;69:93–103.

Kim H. A dual-subsystem model of the brain’s default network: Self-referential processing, memory retrieval processes, and autobiographical memory retrieval. Neuroimage 2012;61:966–77.

Kühn S, Brass M, Haggard P. Feeling in control: Neural correlates of experience of agency. Cortex 2013;49:1935–42. doi:10.1016/j.cortex.2012.09.002

Kwan VSY, Barrios V, Ganis G et al. Assessing the neural correlates of self-enhancement bias: a transcranial magnetic stimulation study. Exp Brain Res 2007;182:379–85.

Laureys S, Owen AM, Schiff ND. Brain function in coma, vegetative state, and related disorders. The Lancet. Neurology 2004;33:537–46.

Legrand D, Ruby P. What is self-specific? Theoretical investigation and critical review of neuroimaging results. Psychol Rev 2009;116:252–82.

Lehmann D, Faber PL, Tel S et al. Reduced functional connectivity between cortical sources in five meditation traditions detected with lagged coherence using EEG tomography. Neuroimage 2012;60:1574–86.

Lenggenhager B, Halje P, Blanke O. Alpha band oscillations correlate with illusory self-location induced by virtual reality. Eur J Neurosci 2011;33:1935–43.

Levy J, Vidal JR, Oostenveld R et al. Alpha-band suppression in the visual word form area as a functional bottleneck to consciousness. Neuroimage 2013;78:33–45.

Llinás RR. I of the Vortex: From Neurons to Self. Cambridge, MA: MIT Press, 2001.

Lou HC, Gross J, Biermann-Ruben K et al. Coherence in consciousness: paralimbic gamma synchrony of self-reference links conscious experiences. Hum Brain Map 2010;31:185–92.

Lou HC, Luber B, Crupain M et al. Parietal cortex and representations of the mental Self. Proc Natl Acad Sci USA 2004;101:5827–32.

Luber B, Lou HC, Keenan JP et al. Self-enhancement processing in the default network: a single-pulse TMS study. Exp Brain Res 2012;223:177–87.

Lutz A, Dunne J, Davidson R. In: Zelazo, PD, Moscovitch, M, Thompson, E (eds), The Cambridge Handbook of Consciousness. Cambridge: Cambridge University Press, 2007.

Lutz A, Lachaux JP, Martinerie J et al. Guiding the study of brain dynamics by using first-person data: synchrony patterns correlate with ongoing conscious states during a simple visual task. Proc Natl Acad Sci USA 2002;99:1586–91.

Mantovani A, Simeon D, Urban N et al. Temporo-parietal junction stimulation in the treatment of depersonalization disorder. Psych Res 2011;186:138–40.

Maris E, Oostenveld R. Nonparametric statistical testing of EEG-and MEG-data. J Neurosci Meth 2007;164:177–90.

Marzetti L, Di Lanco C, Zappasodi F et al. Magnetoencephalographic alpha band connectivity reveals differential default mode network interactions during focused attention and open monitoring meditation. Front Hum Neurosci 2014;8:302.

Metzinger T. Being No One: The Self-Model Theory of Subjectivity. Cambridge, Massachusetts: MIT Press, 2004.

Muthukumaraswamy SD, Carhart-Harris RL, Moran RJ et al. Broadband cortical desynchronization underlies the human psychosomatic state. J Neurosci 2013;33:15171–83.

Nahab FB, Kundu P, Gallea C et al. The neural processes underlying self-agency. Cereb Cortex 2011;21:48–55.

Nolte G. The magnetic lead field theorem in the quasi-static approximation and its use for magnetoencephalography forward calculation in realistic volume conductors. Phys Med Biol 2003;48:3637–52.

Northoff G, Bermpohl F. Cortical midline structures and the self. Trend Cogn Sci 2004;88:102–7.

Northoff G, Heinzel A, de Greck M et al. Self-referential processing in our brain – a meta-analysis of imaging studies on the self. Neuroimage 2006;31:440–57.
Northoff G, Qin P, Feinberg TE. Brain imaging of the self-conceptual, anatomical and methodological issues. Conscious Cogn 2011;20:52–63.

Nydahl O. The Way Things Are: A Living Approach to Buddhism for Today’s World. Winchester, UK: O Books Publishing, 2008.

Oostenveld R, Fries P, Maris E et al. FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. Comput Intell Neurosci 2011;2011:1–9.

Pagnoni G. Dynamical properties of BOLD activity from the ventral posteroomedial cortex associated with meditation and attentional skills. J Neurosci 2012.

Petitmengin C. Describing one’s subjective experience in the second person: An interview method for the science of consciousness. Phenomenol Cogn Sci 2006;5:229–69.

Philippi CL, Feinstein JS, Khalsa SS et al. Preserved self-awareness following extensive bilateral brain damage to the insula, anterior cingulate, and medial prefrontal cortices. PloS One 2012;7:e38413.

Raichle ME, MacLeod AM, Snyder AZ et al. A default mode of brain function. Proc Natl Acad Sci USA 2001;98:676–82.

Ridder DD, Laere KV, Dupont P et al. Visualizing out-of-body experience in the brain. N Engl J Med 2007;357:1829–33.

Ruby P, Decety J. Effect of subjective perspective taking during simulation of action: a PET investigation of agency. Nat Neurosci 2001;4:546–50.

Saggar M, King BG, Zanesco AP et al. Intensive training induces longitudinal changes in meditation state-related EEG oscillatory activity. Front Hum Neurosci 2012;66:256. (September).

Schneider F, Bermpohl F, Heinzel A et al. The resting brain and our self: self-relatedness modulates resting state neural activity in cortical midline structures. Neuroscience 2008;157:120–31.

Seth AK. Interoceptive inference, emotion, and the embodied self. Trends Cogn Sci 2013;17:565–73.

Sierra M, David AS. Depersonalization: a selective impairment of self-awareness. Conscious Cogn 2011;20:99–108.

Sierra M, Nestler S, Jay EL et al. A structural MRI study of cortical thickness in depersonalisation disorder. Psych Res 2014;224:1–7.

Simeon D, Guralnik O, Hazlett EA et al. Feeling Unreal: A PET Study of Depersonalization Disorder. Am J Psych 2000;157:1782–8.

Tal I, Abeles M. Cleaning MEG artifacts using external cues. J Neurosci Meth 2013;217:31–8.

Talairach J, Tournoux P. Co-planar Stereotaxic Atlas of the Human Brain: 3-Dimensional Proportional System – An Approach to Cerebral Imaging. New York: Thieme Medical Publishers, 1988.

Tang YY, Holzel BK, Posner MI. The neuroscience of mindfulness. Neuroscience 2015;16:213–25.

Taylor VA, Grant J, Danellait V et al. Impact of mindfulness on the neural responses to emotional pictures in experienced and beginner meditators. NeuroImage 2011;57:1524–33.

Thompson E. Waking, Dreaming, Being. Self and Consciousness in Neuroscience, Meditation, and Philosophy. New York: Columbia University Press, 2015.

Thompson E, Lutz A, Cosmelli D. (2005). Neurophenomenology: an introduction for neurophsophors. In: Brook, A Atkins, K (eds), Cognition and the Brain: The Philosophy and Neuroscience Movement. New York and Cambridge: Cambridge University Press, 2005, 40–97.

Tsakiris M, Costantini M, Haggard P. The role of the right temporoparietal junction in maintaining a coherent sense of one’s body. Neupropsychologia 2008;46:3014–8.

Tsakiris M, Longo MR, Haggard P. Having a body versus moving your body: neural signatures of agency and body-ownership. Neupropsychologia 2010;48:2740–9.

Vago DR, Silbersweig DA. Self-awareness, self-regulation, and self-transcendence (S-ART): a framework for understanding the neurobiological mechanisms of mindfulness. Front Hum Neurosci 2012;66:296. (October).

Van Der Werf J, Jensen O, Fries P et al. Neuronal Synchronization in Human Posterior Parietal Cortex during Reach Planning. J Neurosci 2010;30:1402–12.

Varela F, Thompson ET, Rosch E. The Embodied Mind: Cognitive Science and Human Experience. Boston: MIT Press, 1991.

Vermersch P. Describing the practice of introspection. J Conscious Stud 2009;16:20–57.

Vogeley K, May M, Ritzl A et al. Neural correlates of first-person perspective as one constituent of human self-consciousness. J Cogn Neurosci 2004;16:817–27.

Williams JMG, Kabat-Zinn J. Mindfulness: diverse perspectives on its meaning, origins, and multiple applications at the intersection of science and dharma. Contemporary Buddhism 2011;12:1–18.

Wraga M, Shephard JM, Church JA et al. Imagined rotations of self versus objects: An fMRI study. Neupropsychologia 2005;43:1351–61.

Zahavi D. Subjectivity and Selfhood Investigating the First-Person Perspective. Cambridge, Massachusetts; London, England: A Bradford Book, MIT Press, 2006.