Event-related Potential and Behavioural Differences in Affective Self-Referential Processing in Long-term Meditators versus Controls

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Abstract

Contemplative practices are thought to modify one's experience of self and fundamentally change self-referential processing. However, few studies have examined the effect of long-term meditation training on brain correlates of self-referential processing. Here we used the self-referential encoding task (SRET) to examine event-related potentials (ERP) during assessment of pleasant and unpleasant self-views in long-term meditators versus age-matched meditation-naïve control participants. Compared to controls, meditators endorsed significantly more pleasant and fewer unpleasant words as self-referential. We also found a between-group difference in the early component of the late-positive-potential (LPP) of the ERP characterised by a higher response to unpleasant versus pleasant words in controls and no difference in meditators. While acknowledging the limitations of a cross-sectional study design, these findings suggest that long-term meditation training might alter self-referential processing towards a more adaptive view of self and neural equivalence towards pleasant and unpleasant self-views. These findings suggest that long-term meditation training may impact brain and behavioural mechanism that support a more flexible and healthy relationship to one's self.

Key words: self-reference, emotion, meditation, SRET, EEG, ERP, late-positive potential

Introduction

A majority of studies on meditation training have focused on how it impacts cognitive faculties such as attention, executive functioning, and emotional regulation (for review see, Chiesa, Calati, & Serretti, 2011; Tang, Hölzel, & Posner, 2015). Contemplative literature both from traditional and contemporary perspectives highlights another psychological process that is critical to mental development and well-being – the practitioner's experience and construct of self (e.g., Albahari, 2016; Anandamurti, 1998; Austin, 2011; Dahl, Lutz, & Davidson, 2015; E. Thompson, 2014; Vago & Silbersweig, 2012). Meditation training is also thought to enhance an equanimous disposition in response to affectively-charged situations (Desbordes et al., 2015). Few neuroscientific studies have, however, explicitly examined how views of self and self-related processing changes with long-term meditation training. In this study we investigate, for the first time, the effect of long-term meditation training on behavioural and ERP indicators of self-referential processing.

Self-referential processing

Humans process information pertaining to themselves preferentially and more deeply compared to information not pertaining to themselves (e.g., Rogers, Kuiper, & Kirker, 1977; Symons & Johnson, 1997). While such preferential processing would have been an evolutionarily adaptive trait for self-preservation, excessive self-focused rumination has been shown to be maladaptive for mental health (e.g. Mellings & Alden, 2000; Watkins & Teasdale, 2001). Thus, developing facility and flexibility in relating to one's self may be a fundamental facet of sustained well-being.

A widely studied behavioural paradigm that demonstrates preference for self-processing is the self-referential encoding task (SRET; Rogers et al., 1977). In the classic version of SRET, individuals are presented a series of words under a self-referential (e.g., judging if words are self-descriptive) and a non-self-referential (e.g., semantic judgement) condition, and are subsequently able to better recall self-referential words (e.g., Symons & Johnson, 1997). Preferential self-referential processing is further amplified when affective, rather than neutral, words are involved (e.g., Fields & Kuperberg, 2012; Fossati et al., 2003; Herbert, Pauli, & Herbert, 2011). The affective version of the SRET that uses both pleasant and unpleasant words has also been used to differentiate healthy from clinical populations. While healthy individuals self-endorse and subsequently recall more pleasant compared to unpleasant words, depressed and anxious populations show the opposite pattern (Derry & Kuiper, 1981; Dozois & Dobson, 2001; Kuiper & Derry, 1982; Lemogne et al., 2010; Rogers et al., 1977; Shestyuk & Deldin, 2010).

Neural correlates of self-referential processing

The human brain has a dedicated network of regions for the preferential processing of self-related information, most prominently the medial frontal-parietal brain network (Fossati et al., 2003; Gusnard, Akbudak, Shulman, & Raichle, 2001; Northoff & Bermpohl, 2004; Ochsner et al., 2004). Self-related emotional information additionally recruits other regions, including the insula and amygdala, as assessed by fMRI (Banks, Eddy, Angstadt, Nathan, & Phan, 2007; Ochsner et al., 2004; Yoshimura et al., 2009). Neural correlates of affective self-referential processing have also been investigated using event-related potentials (ERPs) (Auerbach et al., 2015; Herbert, Herbert, Ethofer, & Pauli, 2011; Herbert, Pauli, et al., 2011; Holt, Lynn, & Kuperberg, 2009; Shestyuk & Deldin, 2010; Watson, Dritschel, Obonsawin, & Jentzsch, 2007). These ERP studies have repeatedly observed differences in the P200 and the late positive potential (LPP). The P200 is an ERP component observed around 200 ms after stimulus-onset over the medial-central electrode sites, and is thought to reflect automatic semantic processing or attentional capture by emotional stimuli (Crowley & Colrain, 2004; Huang & Luo, 2006; Thomas, Johnstone, & Gonsalvez, 2007). The LPP is a more sustained slow wave component of the ERP starting approximately 350 ms following stimulus onset, and is related to sustained attentional and emotional engagement with stimulus content (Dennis & Hajcak, 2009; Hajcak, Dunning, & Foti, 2009; Naumann, Bartussek, Diedrich, & Laufer, 1992; Ruchkin, Johnson, Mahaffey, & Sutton, 1988; Schupp et al., 2000). Thus, these two components are distinct ERP components that might be modified by long-term training in methods that influence attention regulation.

Both P200 and LPP have been found to increase for affective compared to neutral stimuli (Fischler & Bradley, 2006; Foti, Hajcak, & Dien, 2009; Hajcak & Olvet, 2008; Herbert, Junghofer, & Kissler, 2008; Kissler, Herbert, Peyk, & Junghofer, 2007). This difference is also observed when comparing valence of affective self-referential stimuli. However, the findings are mixed. The P200 and LPP have been found to be both *higher* for pleasant compared to unpleasant self-referential words (Auerbach et al., 2015; Herbert, Herbert, et al., 2011; Shestyuk & Deldin, 2010; Watson et al., 2007) as well as *higher* for unpleasant compared to pleasant ones (Fields & Kuperberg, 2012; Herbert, Pauli, et al., 2011; Zhou et al., 2017) in separate studies. ERP differences between pleasant and unpleasant words in the SRET have been used to identify brain patterns that differentiate healthy and clinical populations. Studies have shown that, compared to healthy control groups, individuals who are clinically diagnosed with or who are prone to depression and borderline personality disorder show a much higher difference in ERP P200 responses between unpleasant and pleasant words (Auerbach et al., 2016; Shestyuk & Deldin, 2010), a slightly earlier P100 (Auerbach et al., 2015), and more consistent for the LPP (Auerbach et al., 2015, 2016; Shestyuk & Deldin, 2010; Speed, Nelson, Auerbach, Klein, & Hajcak, 2016).

The LPP has been subdivided into early (~300—600 ms following stimulus onset) and late (>600 ms following stimulus onset) components (Auerbach et al., 2016; Dennis & Hajcak, 2009; Foti et al., 2009). Functionally, the early LPP is implicated in affective encoding, attention and arousal (Naumann et al., 1992; Paulmann, Bleichner, & Kotz, 2013; Schupp et al., 2000), while late LPP is thought to reflect mnemonic aspects of affective processing and prolonged effortful processing (Ruchkin et al., 1988). For affective SRET specifically, group differences between healthy and clinical samples in response to pleasant and unpleasant adjectives have been observed in the early LPP (Shestyuk & Deldin, 2010), late LPP (Auerbach et al., 2016), or both early and late LPP components (Auerbach et al., 2015).

Contemplative training and self-referential processing

There are different types of contemplative disciplines and practices. A common theme across them is that meditation training transforms the practitioner's experience and understanding of self (e.g., Anandamurti, 1998; Dorjee, 2016; Sedlmeier & Srinivas, 2016; Vago & Silbersweig, 2012). As meditation practitioners become more adept with the practice of calming the mind, they gain the capacity to "de-reify" or de-fuse from the contents of one's mind (e.g., Bishop et al., 2004; Lutz, Jha, Dunne, & Saron, 2015). Through such cognitive defusion, practitioners are thought to differentiate themselves from contents of their mind, almost as if being able to experience mental phenomena as a "movie" of transient events (Sedlmeier, 2018). Based on this idea, when a self-referential stimulus is presented, an expert meditator would recognize the stimulus as a mere transient mental object. In contrast, a meditation-naive person might engage in prolonged self-referential rumination. Consistent with this idea, long-term meditators show *reduced* brain activity in midline cortical areas (i.e., medial prefrontal cortex, medial parietal cortex) associated with self-referential processing (Berkovich-Ohana, Glicksohn, & Goldstein, 2012). Short-term mindfulness meditation training, such as an 8-week mindfulness-based stress reduction (MBSR) course, has also been shown to yield reduced activity in cortical midline regions (Berkovich-Ohana et al., 2012; Farb et al., 2007). Moreover, in an affective context, a de-reified stance towards one's mental contents might enable a meditation practitioner to have a less preferential response towards pleasant and unpleasant valence compared to a meditation-naïve individual (Sobolewski, Holt, Kublik, & Wróbel, 2011).

Even before a meditator accomplishes the long-term goal of completely de-fusing from one's mental content, a mere reduction in fusion with self-referential content can help reduce unpleasant or negative feelings towards oneself and help foster an attitude of self-acceptance and self-satisfaction (Jimenez, Niles, & Park, 2010; Ramesh, Sathian, Sinu, & Kiranmai, 2013; B. L. Thompson & Waltz, 2008). For example, one of the ten ethical components of Yogic contemplative practices, which was the tradition of practices undertaken by our long-term meditation group, is the cultivation of satisfaction or contentment with one's current situation (*santosha* in Sanskrit) (Anandamurti, 1981; Bharati, 2001; Van Ness, 1999). Such a self-satisfied attitude can promote positive mental-health, and could be one of the ways mindfulness meditation training helps alleviate symptoms of anxiety and depression (Hofmann, Sawyer, Witt, & Oh, 2010; Jimenez et al., 2010; Kuyken et al., 2015; Segal et al., 2010). An fMRI study examining pre– versus post–MBSR changes in neural correlates of affective SRET in adults with social anxiety disorder showed decreased endorsement of unpleasant and increased endorsement of pleasant views of oneself accompanied by greater responses in brain regions associated with top-down attention, and reduced activation of the cortical midline (Goldin, Ramel, & Gross, 2009). However, thus far no studies have investigated whether much longer-term contemplative training is associated with brain and behavioural changes in affective self-referential processing, specifically when targeting three different ERP components (i.e., P200, early and late LPP) that might reflect distinct cognitive-affective processes.

The Present Study

The goal of this study was to investigate whether, compared to a meditation-naïve control group, long-term meditators are characterised by differences in the P200 and LPP components of the ERP during self-referential processing of pleasant and unpleasant adjectives. To investigate this question, we recorded the EEG while participations performed the SRET in a laboratory setting. We recruited long-term meditators from a Yogic contemplative system where self-transformation is the essential theme of the training (see Methods). We predicted that, compared to the meditation-naive control group, long-term meditators would show distinct behavioural and brain differences during the SRET. For behavioural responses, based on previous observations of self-views in mentally healthy individuals, we expected that both groups would endorse significantly more pleasant than unpleasant adjectives as self-referential (Derry & Kuiper, 1981; Dozois & Dobson, 2001; Kuiper & Derry, 1982; Lemogne et al., 2010; Rogers et al., 1977; Shestyuk & Deldin, 2010). Moreover, if long-term meditators have a more self-satisfied and self-accepting outlook, they would endorse significantly more pleasant adjectives (like *satisfied*, *joyful*, etc.) and fewer unpleasant adjectives (like *sad*, *depressed*, *anxious*, etc.) as self-referential compared to the control group (Goldin et al., 2009). For ERP responses during the SRET, we had two hypotheses, 1) long-term meditators would show a larger increase in the difference between pleasant and unpleasant adjectives for the P200, early-LPP and late-LPP components compared to the control group, paralleling previous comparisons between healthy and depressed/anxious individuals (Auerbach et al., 2015, 2016; Shestyuk & Deldin, 2010; Speed et al., 2016), and/or, 2) long-term meditators would not show a difference in P200, early-LPP and late-LPP components between pleasant and unpleasant adjectives reflecting a more "neutral" experience of valence, while the control group would (in either direction, as the directionality is unclear from past research). The two hypotheses could also be true simultaneously if the control group showed a higher response to unpleasant compared to pleasant adjectives, but the meditators did not show a difference between the two. Both hypotheses will be tested primarily through a *group* (meditator, control) by *valence* (pleasant, unpleasant) interaction in the three ERP components.

Methods

Participants

Thirteen long-term meditators (4 females) from the *Ananda Marga* community (Mean age = 56.8 years, *SD* = 12.3 years) with a mean of 32.2 years of meditation training (*SD* = 9.7) and fifteen (6 females) age-matched controls (Mean age = 53.5 years, *SD* = 14.2 years) with no meditation experience participated in the study. Previous ERP studies of affective self-referential processing have used typical samples-sizes of 15–25 (e.g., (Herbert, Pauli, et al., 2011; Shestyuk & Deldin, 2010)), while ERP studies on long-term meditators have used typical sample-sizes of 13–17 (e.g., (Cahn, Delorme, & Polich, 2013; Sobolewski et al., 2011).

The two groups did not differ in years of formal education (meditators: mean = 15.9 years, SD = 3.0; controls: mean = 16.4 years, SD = 2.1; Wilcoxon rank-sum = 171.5; $p = 0.64$, two-tailed). Nine out of thirteen individuals from the meditator group were monastics, many of whom reported no direct source of income besides a subsistence support from non-monastic practitioners. The meditator group (after including the subsistence-level support for monastics) thus had a significantly lower income level in the year prior to the study compared to the controls (Wilcoxon rank-sum = 69.5; $p = 0.011$, two-tailed).

Participants reported no history of psychiatric or neurological disorders. All participants either had English as their first language or were fluent speakers for over 30 years. All participants provided written informed consent in compliance with the Institutional Review Board at the University of California Davis. All participants reported having normal or corrected-to-normal visual acuity.

Long-term meditators were recruited from the San Francisco Bay Area and national mailing lists of the *Ananda Marga* (sanskrit for Path of Bliss) meditation community. Long-term meditators were included if they had greater than 10 years of regular practice of at least 1 hour per day, although most were meditating 2–3 hours daily for the past 10 years. Age-matched meditation-naive control participants were recruited locally from the Sacramento and Davis areas via online forums and fliers posted in public libraries and at UC Davis. Only two of the control participants had brief experience (less than 2 months in their entire life) with meditation or yoga postures.

Ananda Marga is a Tantric Yogic system originating in India. Practitioners engage in multiple daily practices including moral guidelines (*yama* and *niyama*), yogic postures (*asanas*), controlled breathing (*pranayama*), focused attention meditation on a phrase (*mantra*) whose meaning deals with self-transformation, and nondual meditation (*dhyana*). In the *Ananda Marga* system, the combination of different practices work synergistically towards the ultimate goal of "self-realisation" where one's feeling of an egocentric sense of self is expanded into a transpersonal self-concept, which is in turn merged into a transcendental "Self" beyond mental perturbations (Anandamurti, 1998). In addition to formal sitting meditation, practitioners are highly encouraged to engage in social service to inculcate compassion towards all beings.

Self-Referential Encoding Task

The SRET was administered via a computer using Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com) on a monitor (21-inch diagonal) kept at a distance of 74 cm from the participant (Auerbach et al., 2015; Speed et al., 2016) . In the SRET, we presented 60 trials with 30 pleasant and 30 unpleasant trait adjectives (see Supplementary Material for words) taken from the Affective Norms for English Words (ANEW) (Bradley & Lang, 1999). Words were chosen so that they were matched for valence ($t(58) = -0.38$, $p = 0.70$), arousal ($t(58) = -1.54$, $p = 0.12$), word length ($t(58) = 0.70$, $p = 0.48$) and frequency ($t(58) = 1.39$, $p = 0.17$). Presentation of words was pseudo-randomised. Each trial included a fixation cross presented in the centre of the screen for 500 ms, a single word for 1000 ms, a fixation cross for 500 ms, and then a question, "Does this word describe you?" Participants were required to respond to this question by pressing the left or right mouse buttons for 'Yes' and 'No,' respectively. A response was mandatory before the next trial could begin. The response was followed by the fixation cross, which remained on the screen for 500 ms before the appearance of the next word. Words were presented in white on a black background. Height of the words was 5 cm. Prior to beginning the experiment, participants underwent three practice trials using affectively neutral words to familiarize themselves with the task procedures. We confirmed that participants understood the task instructions before starting the SRET. If the task was not clear to the participants following the three practice trials, we described the task again and redid the three practice trials.

Behavioural Analysis

Self-endorsement was calculated separately for the pleasant (n = 30) and unpleasant words (n = 30) as the percentage of words the participant endorsed as self-descriptive. The distribution of percent pleasant and unpleasant words endorsed by the participants was non-normal (Kolmogorov-Smirnov test, $p < 0.001$). We therefore used non-parametric tests to assess group differences. Wilcoxon signed-rank test was used to assess if there was a difference between percent pleasant and unpleasant endorsement for each group. Mann–Whitney–Wilcoxon rank-sum test was used to assess if there was a difference in percent endorsed pleasant and unpleasant words between the two groups.

EEG data acquisition

Continuous EEG data was acquired at a sampling rate of 1000 Hz using a 32-channel ActiChamp (Brain Products, Germany) while participants completed the SRET. The ActiChamp system uses active electrodes that improve the signal-to-noise ratio at each electrode site. Each channel was ensured to have an impedance below 16 kΩ before beginning the experiment. The Presentation software was synchronised to the EEG system by sending TTL pulse triggers through an LPT (parallel) port from the computer used to present stimuli to the data collection computer at the time of each word's onset.

EEG analysis

EEG analysis was conducted using functions provided in EEGLAB (Delorme and Makeig, 2004) and custom MATLAB code. Data were first downsampled to 250 Hz, band-pass filtered from 0.05 to 30 Hz using the functions provided in EEGLAB, and then re-referenced (offline) to the average of TP9 and TP10 (i.e., average mastoid reference).

We used Independent Component Analysis (ICA) implemented via EEGLAB (Delorme & Makeig, 2004) to remove ocular and muscle artefacts (Delorme, Sejnowski, & Makeig, 2007). The components were rejected manually by inspecting them for typical signatures of eye-blinks, horizontal eye-movements, muscular artifacts (at lateral peripheral channels), and bad channels from each subjects' dataset (Chaumon, Bishop, & Busch, 2015; Jung et al., 2000). All components were removed by the same individual (the first-author). On average, we removed 10 components per participant. Following component removal, trials with artefacts were identified automatically (voltage exceeding ±100 μV within a 200 ms window) and were excluded from further analysis. In addition, we visually inspected the remaining trials to detect the presence of other artefacts. Overall, only 5 such trials were excluded from analysis across all participants.

Event-related potentials. To compute event-related potentials (ERPs) we performed baseline subtraction of the mean EEG response within a 250 ms window preceding stimulus onset for each trial and then averaged all included trials between –250 and 1300 ms around the stimulus onset, separately for pleasant and unpleasant words, within each participant. To aid visualisation of ERPs in Figure 2 we additionally smoothed the data with a 52 ms boxcar window (statistically the smoothing had little impact on our results). P200 was quantified by averaging the ERP between 150—250 ms from trial onset (Crowley & Colrain, 2004), while the early and late LPPs were averaged between 300–500 ms and 800–1000 ms from stimulus onset respectively (Auerbach et al., 2015; Keil et al., 2002; Speed et al., 2016, 2016). The three ERP components are typically observed over medial frontal-central-parietal locations. We therefore evaluated them by averaging over, CP1, CP2, Cz, FC1, FC2 (Crowley & Colrain, 2004; Cuthbert, Schupp, Bradley, Birbaumer, & Lang, 2000; Foti et al., 2009; Hajcak et al., 2009; Herbert, Pauli, et al., 2011; Schupp et al., 2000; Speed et al., 2016).

Time-frequency analysis. As with the ERPs, we first averaged each trial's time-series over the channels CP1, CP2, Cz, FC1, FC2, and then performed time-frequency decomposition on it using MATLAB's *spectrogram* function, which calculates the short-term Fourier transform of the signal. The time-frequency decomposition was performed starting at stimulus onset to 1300 ms in the frequency range 0.05—30 Hz using a hamming window of 372 ms with a 364 ms overlap between consecutive time samples. We calculated the difference of the time-frequency decomposed signal between pleasant and unpleasant words for each group, and then the difference of that difference between the two groups. To obtain time-frequency regions that were reliably different within and between groups, we evaluated 5000 random permutations of the differences as our null hypothesis, and then used maximum pixel based thresholding at α = 0.05 (Cohen, 2014).

Analysis of association between behavioural and brain response

To evaluate the contribution of self-endorsements and LPP in differentiating between the two groups, we performed a binomial logistic regression using the MATLAB function *glmfit*. We also performed cross-validation using a 4-fold classifier (10,000 shuffles) to determine the accuracy of the logistic regression model in differentiating between the two groups.

To investigate the relationship between behavioural and neural response we used mixed models as implemented in R (Bates, Mächler, Bolker, & Walker, 2014; Team, 2013). Mixed models can account for both random and fixed effects while allowing a continuous dependent variable to be used as an "independent" mediator variable for another dependent variable. We modeled *group*, *valence*, and LPP amplitude as fixed effects along with a random intercept for each subject to predict behavioural self-endorsements. As our dependent variable was a positive definite value (self-endorsement percentage), we used generalised linear mixed models with the family parameter set to *binomial* and weight parameter set to the number of trials (30 per valence condition). We ran this model through a type II analysis of variance, which uses Wald χ^2 tests for obtaining statistical significance on the fixed effects. To get the model fits and trending curves, we used the *plot_model* function available in the *sjPlot* R package, which uses the *ggpredict* function of the *ggeffects* R package to obtain predicted values of regression models (Lüdecke, 2018b, 2018a).

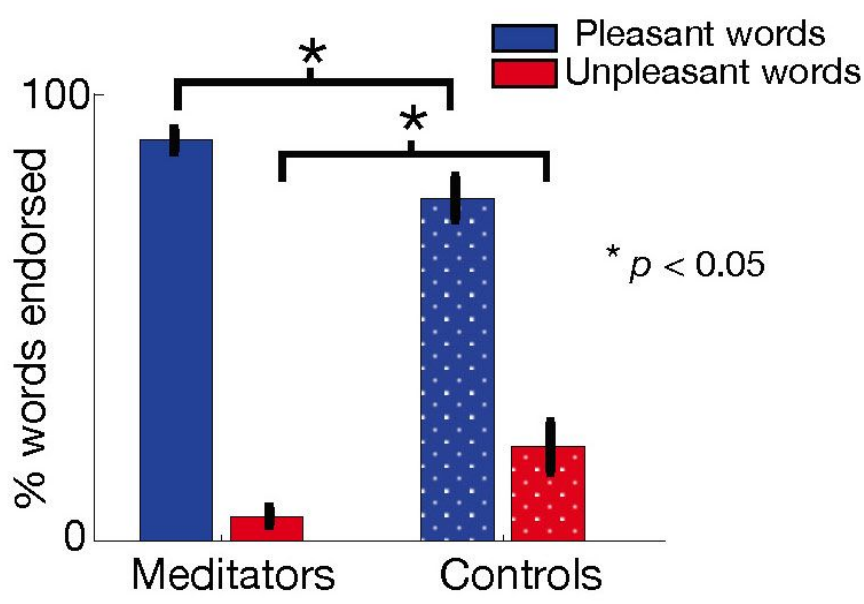

Figure 1. Percent of self-endorsed pleasant (blue) and unpleasant (red) words for the two groups, long-term meditators and controls. Error-bars show standard errors of the means.

Results

Behavioural Responses

Figure 1 shows the percent of pleasant and unpleasant words endorsed as self-referential. As the self-endorsement percent data was non-normal, we performed non-parametric tests to assess statistical significance (see Methods). Both long-term meditators (Mann–Whitney–Wilcoxon signed-rank = 91; $p < 0.001$, two-tailed) and controls (Mann–Whitney–Wilcoxon signed-rank = 102; $p < 0.001$, two-tailed) self-endorsed pleasant adjectives significantly more than unpleasant adjectives. The long-term meditators self-endorsed significantly fewer unpleasant adjectives (Wilcoxon rank-sum = 142; $p = 0.027$, two-tailed) and significantly more pleasant adjectives compared to the control group (Wilcoxon rank-sum = 231; $p = 0.049$, two-tailed).

As an exploratory analysis, we compared each of the 60 words between the two groups. Supplementary Figure 1 shows the proportion of individuals that self-endorsed each word in the two groups. To compare each word, we ranked each endorsed word by an individual as 1 and non-endorsed word as 0. We used a two-tailed Wilcoxon rank-sum test to obtain all words that were self-endorsed statistically differently by the groups at $p < 0.05$. Compared to the control group, significantly more meditators self-endorsed the words *satisfied*, *radiant*, *dignified*, *outstanding* and *smooth*, and significantly fewer meditators self-endorsed the words *rigid*, *depressed*, *rejected*, *sad*, and *sinful*.

Evoked Response Potentials

Figure 2A shows the ERPs for pleasant and unpleasant valenced adjectives for the long-term meditator (solid lines) and control (dashed lines) groups. For the P200 (Figure 2B; left shaded region in Figure 2A), a 2 *group* (meditators, controls) x 2 *valence* (pleasant, unpleasant) mixed-ANOVA yielded no significant interaction ($F(1, 26) = 2.33$, $p = 0.14$), main effects of group ($F(1, 26) = 0.0001$, $p = 0.99$), or valence ($F(1, 26) = 0.73$, $p = 0.40$).

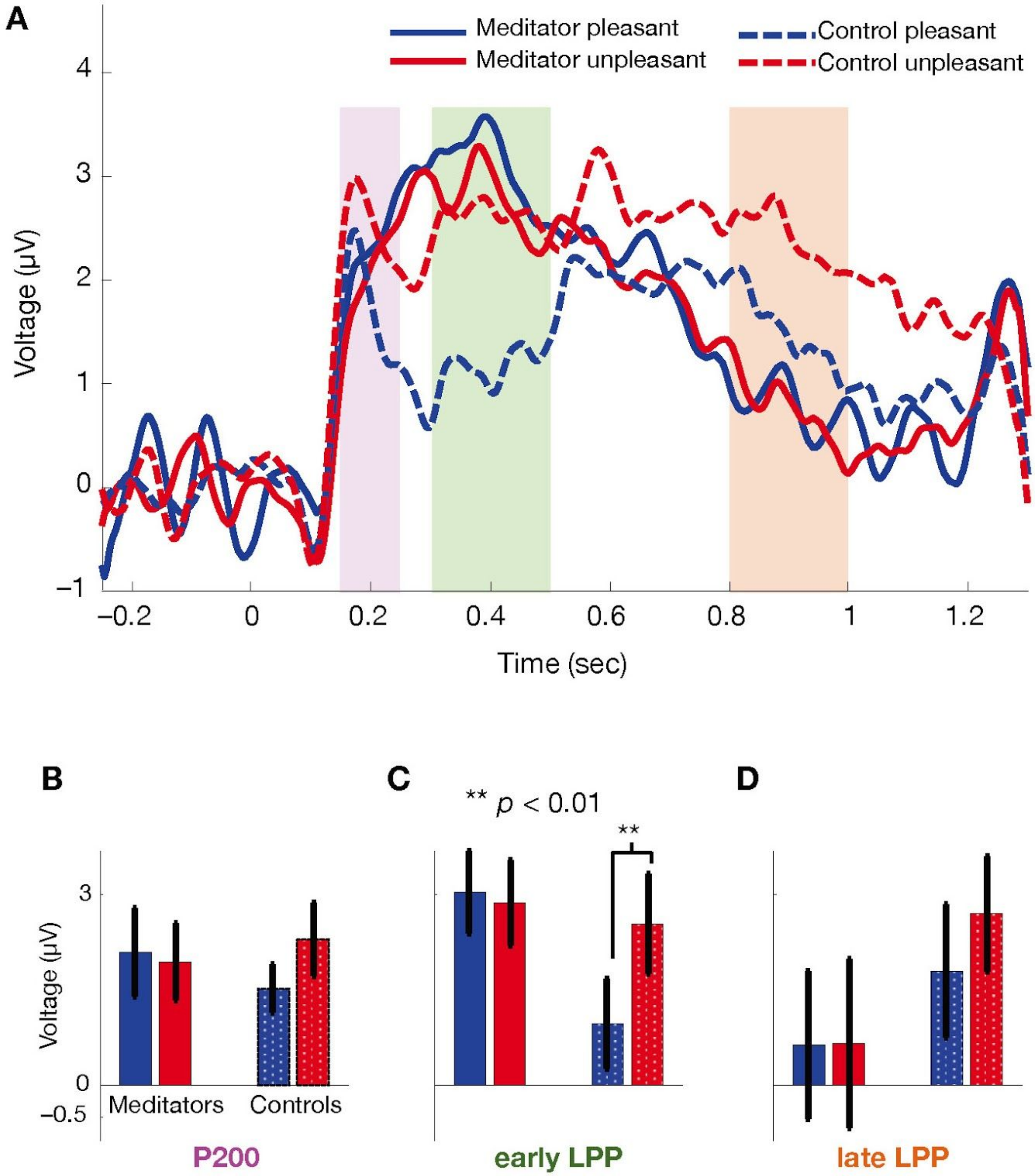

Figure 2. A) ERPs for pleasant (blue lines) and unpleasant (red lines) words presented during the SRET at medial frontal-central channels for long-term meditators (solid lines) and controls (dashed lines). B) P200 amplitudes within the magenta shaded region in A (pleasant and unpleasant words as blue and red bars respectively). C) early LPP amplitudes within the green shaded region. D) late LPP amplitudes within the orange shaded region.

For the *early* LPP (Figure 2C; middle shaded region in Figure 2A), a 2 *group* (meditators, controls) x 2 *valence* (pleasant, unpleasant) mixed-ANOVA yielded a significant interaction between group and valence (F(1, 26) = 6.39, p = 0.018, η_p^2 = 0.20). Neither the main effect of valence (F(1, 26) = 2.35, p = 0.14) nor group (F(1, 26) = 1.13, p = 0.30) was significant. Post-hoc analyses on the early-LPP revealed that the control group had significantly greater response for the unpleasant compared to pleasant words (t(14) = –3.12, p = 0.007), while the meditator group did not (t(12) = 0.65, p = 0.53). There was a trend for a lower LPP in response to pleasant words in the control compared to the meditator group (t(26) = 1.97, p = 0.058) but no difference between groups for unpleasant words (t(26) = 0.09, p = 0.93).

For the *late* LPP (Figure 2D; right shaded region in Figure 2A), there was no interaction effect (Figure 2D; F(1, 26) = 1.82, p = 0.19), and no main effects of group (F(1, 26) = 0.56, p = 0.46) and valence (F(1, 26) = 1.63, p = 0.21).

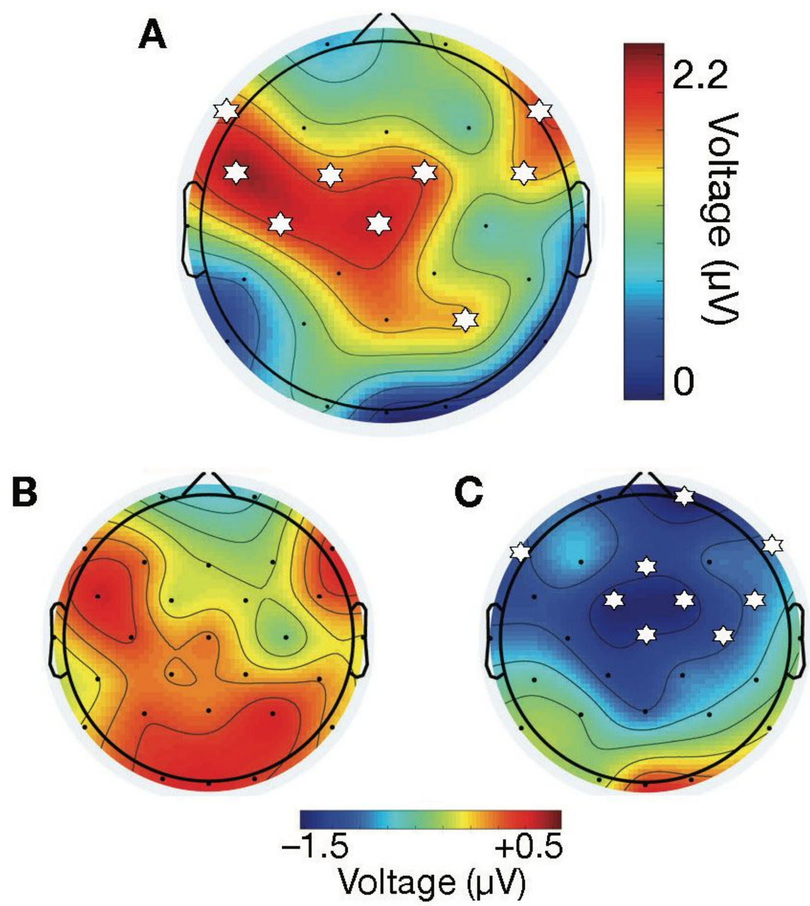

Figure 3. Topography of the A) early-LPP interaction effect, and the difference between pleasant and unpleasant words in the B) long-term meditator, and C) control groups (stars indicate channels with p < 0.1, FDR corrected).

Figure 3A shows the topography of the *group* x *valence* interaction effect plotting the difference between pleasant and unpleasant word evoked early LPPs with meditators minus controls. As the interaction effect was not significant at $\alpha = 0.05$ after false-discovery-rate (FDR) correction for multiple comparisons, we mark channels where the interaction effect survived a more lenient FDR-corrected threshold of $p < 0.1$. The effect was observed across bilateral and medial frontal channels. Post-hoc topographies showed that the control participants responded more to unpleasant than pleasant adjectives over medial and bilateral frontal channels (Figure 3C). When doing the same comparison in long-term meditators, we observed that pleasant adjectives evoked a greater early LPP than unpleasant ones over lateral-frontal and occipital channels, though none of the channels survived an FDR-corrected $p < 0.1$ (Figure 3B).

Association between Behavioural and ERP Responses

As both behavioural self-endorsements and early-LPP were different between groups, we tested if the two effects differentiated groups independently. We performed a binomial logistic regression to predict the factor *group* with two predictors: difference between pleasant and unpleasant self-endorsements, and the difference between pleasant and unpleasant early-LPP, both of which were reduced in controls. We found that LPP (t = –2.39; $p = 0.025$) and self-endorsements (t = –2.47; $p = 0.021$) both predicted *group* significantly, suggesting that brain and behaviour independently differentiated the groups. A cross-validation procedure on the logistic regression analysis using both LPP and self-endorsements to predict each participant's group yielded a classifier performance of 64.2%.

We then performed further exploratory analyses to investigate a potential relationship between the behavioural self-endorsements and the early-LPP response using generalised linear mixed models; the two levels of *valence* (pleasant and unpleasant) were included in the model along with the *group* factor (see Methods). We observed a significant three-way interaction of *group*, *valence*, and early-LPP amplitudes (Figure 4; $\chi^2(1) = 30.10$, $p < 0.001$). Visual inspection revealed that this interaction was due to the two groups having a different relationship between early-LPP and self-endorsements for the two valence conditions. This was confirmed using a post-hoc generalised linear mixed model with two factors, *valence* and early-LPP amplitude, separately for the meditator and control groups. The meditator group showed a significant two-way interaction between *valence* and early-LPP amplitude in predicting self-endorsements where higher LPPs were associated with increasing pleasant self-endorsements and decreasing unpleasant self-endorsements (Table 1; $\chi^2(1) = 16.81$, $p < 0.001$). For the control group, on the other hand, increased LPPs were associated with decreasing pleasant self-endorsements and increasing unpleasant self-endorsements ($\chi^2(1) = 36.21$, $p < 0.001$).

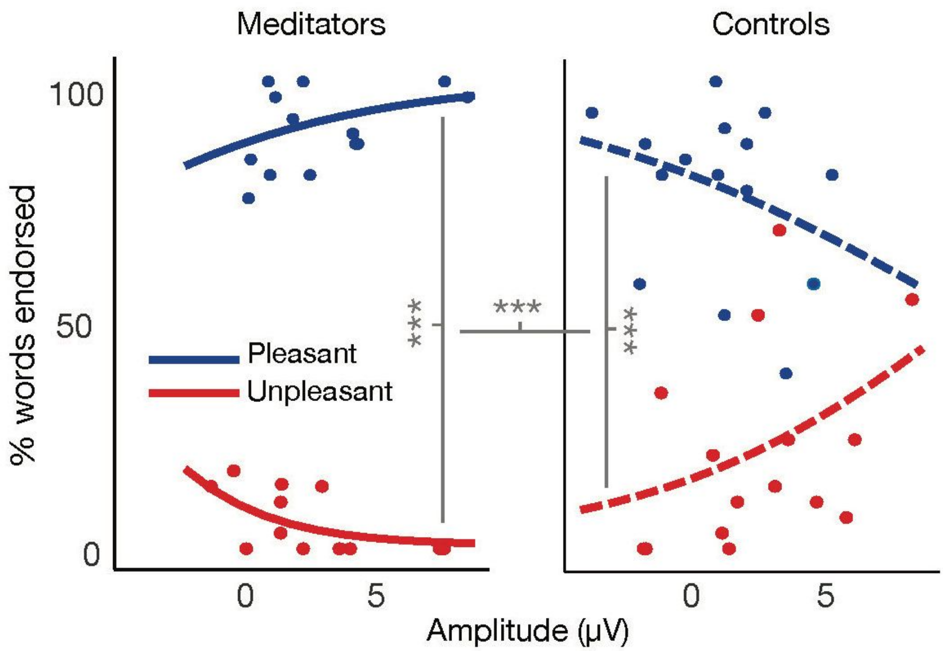

Figure 4. Fit to a generalised linear mixed model showing the relationship between self-endorsement for pleasant (blue) and unpleasant (red) adjectives, and early-LPP for long-term meditators (solid lines) and controls (dashed lines). Dots indicate individual participants. ***$p < 0.001$.

Table 1. 3- and 2-way interactions and main effects in the mixed-effects GLM

Effect	χ^2**(1)**	***p*value**
3-factor mixed-GLM (*group, valence, lpp*)		
*group*x *valence*x *lpp*	30.10	$<10^{-7}$
*group*x *valence*	31.02	$<10^{-7}$
*valence*x *lpp*	7.86	<0.01
*group*x *lpp*	0.01	0.91
group	2.64	0.10
valence	413.88	$<10^{-15}$
lpp	1.85	0.17
2-factor mixed-GLM (*valence, lpp*) in meditators		
*valence*x *lpp*	12.64	0.0004
valence	224.09	$<10^{-15}$
lpp	0.04	0.84
2-factor mixed-GLM (*valence, lpp*) in controls		
*valence*x *lpp*	22.10	$<10^{-5}$
valence	209.64	$<10^{-15}$
lpp	2.02	0.15

Time-frequency decomposition

We performed exploratory time-frequency analysis on our data, testing for differences in valence within the two groups, and differences between the groups in the difference of pleasant and unpleasant valence (analogous to the significant mixed-ANOVA interaction effect that we described above). Figure 5A–B show the difference in the time-frequency decomposed signal between pleasant and unpleasant words for the two groups. In the control group (Figure 5A), we found multiple time-frequency clusters where unpleasant words evoked significantly ($p < 0.05$) higher power than the unpleasant words. The biggest of these clusters was in the delta frequency range (<3 Hz) between 200—600 ms following stimulus onset, corresponding to P200 and early LPP portions of the ERP. There were also clusters in the theta (3—6 Hz), alpha

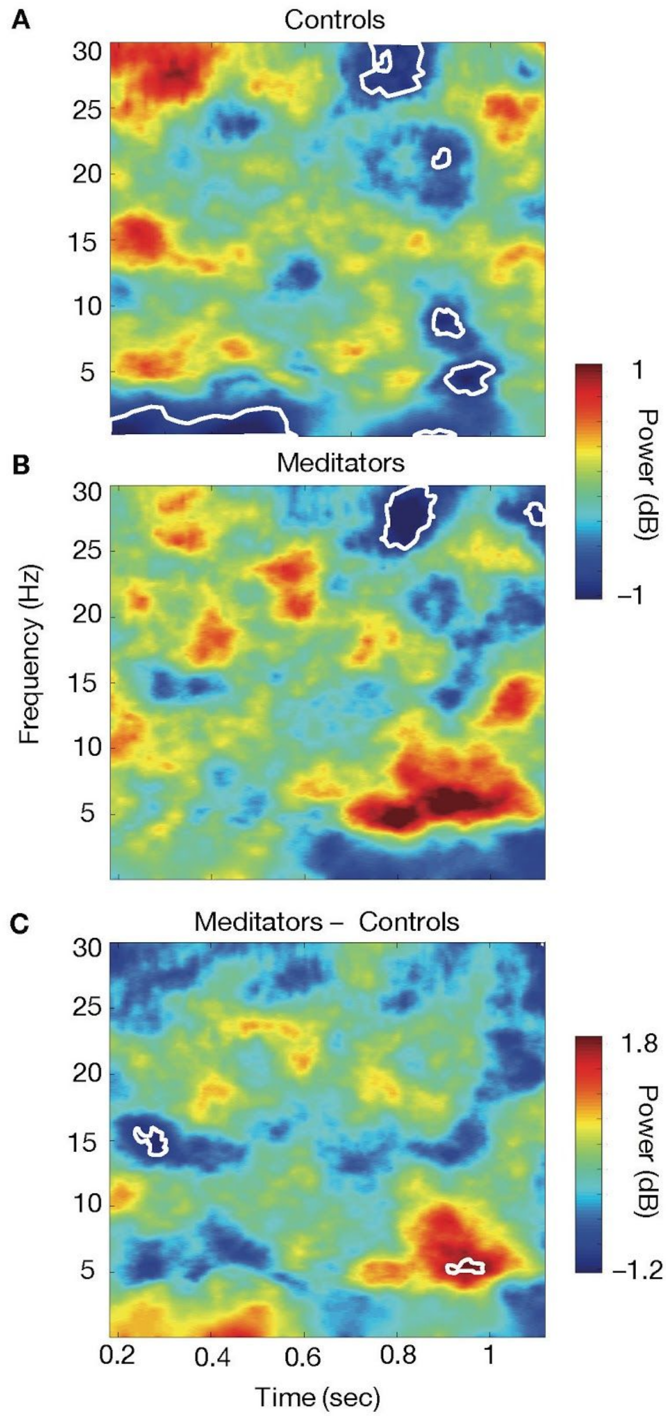

Figure 5. Time-frequency plots of A) the difference in power between pleasant and unpleasant words in controls, B) the difference between pleasant and unpleasant words in meditators, C) the difference between A and B. Time on the axis is from the onset of the words. The outlines encompass significant clusters ($p < 0.05$).

(7.5—10 Hz), beta (20—22 Hz), and lower gamma (26—30 Hz) frequencies around 750—1000 ms following stimulus onset corresponding to a late LPP. In the meditator group (Figure 5B), there was a significant cluster of pleasant < unpleasant around 750—900 ms following stimulus onset in the lower gamma band (25—30 Hz) similar to the control group. When taking the difference between the meditator and control group of the difference value between pleasant and unpleasant valence, we found two significant clusters (Figure 5C): one occurring late (900—1000 ms following stimulus onset) in the theta frequency band (4—6 Hz) where the difference of pleasant minus unpleasant adjectives was greater in meditators compared to controls, and another occurring early (240—300 ms following stimulus onset) in the lower beta frequency range (14—16 Hz) where the same difference was greater in the control group compared to the meditators.

Discussion

Our goal was to investigate the behavioural and brain correlates of affective self-referential processing in long-term meditators compared to age-matched meditation-naive controls. We found that 1) long-term meditators self-endorsed fewer unpleasant and more pleasant adjectives compared to the control group, 2) meditators and controls differed in their early-LPP response, with controls responding to fewer pleasant than unpleasant words, while meditators were not characterised by this difference, and 3) meditators had an association between early-LPP and self-endorsement of more pleasant and fewer unpleasant adjectives, while controls showed the opposite pattern.

Previous studies have shown that healthy individuals tend to self-endorse more pleasant than unpleasant words (e.g., Auerbach et al., 2015; Derry & Kuiper, 1981; Goldin et al., 2009; Kuiper & Derry, 1982). This is in contrast with individuals suffering from depression, anxiety, and borderline personality disorder who tend to self-endorse more unpleasant than pleasant words (Derry & Kuiper, 1981; Dozois & Dobson, 2001; Kuiper & Derry, 1982; Thurston, Goldin, Heimberg, & Gross, 2017). In the current study, long-term meditators endorsed significantly more pleasant and significantly fewer unpleasant words than the controls, reflecting more positive and adaptive self-views. Such behavioural differences in self-views of our group of meditators, when considering their contemplative tradition of meditation training, could be an outcome of several underlying factors, including: 1) A more self-content attitude towards life (for example, while endorsing words such as *satisfied*, *confident*, *grateful*, *secure*, and not endorsing words like *helpless*, *displeased*, *insecure*, etc.). This is codified most prominently in *Ananda Marga* practices (which our long-term meditator group engaged in) through the self-directed ethical principle (or *niyama*) of *santosha*, meaning satisfaction or contentment (Anandamurti, 1981). 2) Specific pleasant qualities that they experience in their practice (for example, a greater sense of being *patient*, *joyful*, *relaxed*, and reduced sense of being *anxious*, *depressed*, *unhappy*, *angry*, etc.). The meditator group engaged practices that are said to induce experiences of joy and bliss (*ananda*). And while attachment to such experiences is considered a hindrance on the path, their experience leading to a continued engagement with practice is generally encouraged in Yogic contemplative traditions (Bharati, 2001). 3) Qualities that may be considered a combination of experience through practice as well as part of the socially-embedded values that the practitioners were conforming to while responding (for example, in endorsing words like *moral*, *wise*, *radiant*, *dignified*, and not endorsing *sinful*, *helpless*, *useless*, *rejected*, etc.).

Visual inspection revealed a difference in ERPs for long-term meditators compared to controls around 200 ms following stimulus-onset over medial-central electrodes reflecting sustained differences in cognitive-affective processing (Figure 2A). While the meditators' response did not seem to differ between pleasant and unpleasant words, non-meditators were characterised by a reduced LPP to pleasant compared to unpleasant words.

For the early-LPP component, the difference between pleasant and unpleasant words between groups was statistically significant widely across medial and bilateral frontal channels. Previous MRI-based studies of longitudinal contemplative training have found similar neural loci corresponding to self-referential processing (Goldin et al., 2009; Lumma, Valk, Böckler, Vrtička, & Singer, 2018). Post-hoc topographies revealed that the effect was primarily driven by the control group's reduced response to pleasant compared to unpleasant words over medial and bilateral frontal-central electrode sites suggesting lower pleasant self-view processing in the control group (Northoff & Bermpohl, 2004).

The opposite pattern of early-LPP for pleasant vs. unpleasant words between groups is akin to findings between healthy vs. clinical populations using the SRET (Auerbach et al., 2015, 2016; Shestyuk & Deldin, 2010; Speed et al., 2016). In these past studies, individuals diagnosed with or prone-to depression and borderline personality disorder exhibited a smaller difference between pleasant and unpleasant LPPs compared to healthy populations, i.e., the value of pleasant- minus unpleasant-word-evoked LPP was smaller in the clinical group. In this context, our results suggest that meditators have a "healthier" neural response than the healthy control group, as the latter also had a smaller pleasant minus unpleasant value of the LPP than the former.

While the control group self-endorsed more pleasant than unpleasant words, their early-LPP response was in the opposite direction reflecting a "self-related negativity bias". Past studies investigating self-related affect in healthy groups have been ambiguous with regard to whether there should be a positivity (towards pleasant words) and negativity (towards unpleasant words) bias in the LPP response with some studies showing higher LPPs for pleasant compared to unpleasant self-referential words (e.g., Auerbach et al., 2015; Herbert, Herbert, et al., 2011; Shestyuk & Deldin, 2010; Watson et al., 2007), while others show a self-related negativity bias of the kind we observed (e.g., Bernat, Bunce, & Shevrin, 2001; Fields & Kuperberg, 2012; Herbert, Pauli, et al., 2011; Zhou et al., 2017). This negativity bias might also be related to the age the control group (mean = 54 years). Only one previous study has been conducted on a middle-to-old age group (mean = 43 years), which also showed a negativity bias (Zhou et al., 2017).

In contrast to the control group, the meditators did not respond differently to pleasant and unpleasant words. While being aware of the caveats in interpreting statistical null effects, we briefly discuss this due to its meaningfulness in contemplative research. *Ananda Marga* practitioners aim to attain a state of pure phenomenal awareness or a

"witnessing self" beyond mental perturbations through daily long-term practice. In the attainment of this long-term goal, as one's practice advances, they are said to gradually let go of the idea of an egocentric self-identity (Anandamurti, 1998). Self-related affect is evaluated from a more distanced (e.g., a third person) perspective that helps cultivate an equanimous disposition (e.g., Anandamurti, 1994). Thus, we would expect a more similar response to pleasant and unpleasant self-views, of the kind we observed in our study.

Our exploratory time-frequency analysis investigated spectral measures in the EEG. Consistent with the overall higher ERP to unpleasant compared to pleasant adjectives for the control group, we found multiple significant time-frequency clusters with higher power for unpleasant compared to pleasant adjectives. Some of these differences likely corresponded to the P200 and early LPP (at low frequencies), and late LPP (spanning a larger spectrum of frequencies). Greater power for unpleasant vs. pleasant adjectives was also observed in the mediators at high frequencies similar to control group, suggesting that such a response might reflect generally increased processing of unpleasant compared to pleasant valence, regardless of meditation training. Unlike the ERPs, we did not find a significant effect between groups between pleasant and unpleasant valence during the time-range of the early LPP (i.e., corresponding to the interaction effect). We suspect this could be due to the difference in valence between the groups becoming “diffused” over a larger range of time and frequencies, and therefore not reaching statistical reliability. The time-frequency decomposition showed a similar difference between the groups in the time-range of the late LPP, which was not observed in the ERP probably due to it not being in the delta band. The ERP and time-frequency analysis therefore seem to offer complementary information and recommended to be included in future research. Overall, our time-frequency analysis indicates that the previously reported differences in early and late LPPs for affective processing (e.g., Auerbach et al., 2016; Dennis & Hajcak, 2009; Foti et al., 2009) might also involve different frequency signatures. The early LPP might differentiate valence primarily at low frequencies (<3 Hz). The late LPP might span a larger spectrum of frequencies, of which, the theta band is more amenable to manipulation (for example, via meditation training), while other frequencies are not.

In addition to group differences in behaviour (self-endorsement) and brain (early-LPP), our exploratory results also show that the two groups markedly differ in the relationship between brain and behaviour. While in the meditator group, increasing LPP response was associated with higher pleasant and lower unpleasant self-endorsements, the control group showed the opposite pattern. This indicates that the LPP could be reflecting two different sub-processes, one where the neural mechanism underlying higher LPP is maladaptive and another where it is adaptive. The presence of two different processes could also explain the ambiguity of positivity and negativity bias in LPP across different studies of self-related affect (Fields & Kuperberg, 2012; Herbert, Herbert, et al., 2011; Herbert, Pauli, et al., 2011; Watson et al., 2007). Future studies can be designed to disentangle the presence of these complementary dual processes.

Past clinical research has shown that maladaptive self-views are a hallmark of clinical disorders such as depression and anxiety (Beck, 1967; Blackburn & Eunson, 1989; Blaney, 1986; Williams, Healy, Teasdale, White, & Paykel, 1990). Processing of unpleasant views of the self has been shown to be heightened using SRET during such disorders (Derry & Kuiper, 1981; Dozois & Dobson, 2001; Kuiper & Derry, 1982; Lemogne et al., 2010; Thurston et al., 2017). Contemplative therapeutic programs like mindfulness-based stress reduction (MBSR) and mindfulness-based cognitive therapy have been shown to be effective alternatives to psychotropic medication for treating symptoms of depression and anxiety (Hofmann et al., 2010) and for the prevention of relapse in depression (Kuyken et al., 2015; Segal et al., 2010). Our findings indicate that the improvement of such disorders with mindfulness and meditation could occur by shifting one's focus to more adaptive self-views (Goldin et al., 2009; Thurston et al., 2017).

One limitation of our study is that even though the two groups were matched for demographic factors such as age and education, the differences between them may not have been due to meditation training but rather to a self-selection bias of the meditator group, or other types of lifestyle choices made by the groups throughout their lives (e.g., many of the participants of the meditator group lived a monastic lifestyle, all of them followed a vegetarian diet during the course of their practice, etc.). This is a shortcoming of any cross-sectional study on long-term contemplative training. Any interpretation of the present results, therefore, should be made with caution and in relation to the limitations of a cross-sectional design. However, considering that contemplative practices and the lifestyle choices undertaken by the meditator group used in our study were developed within a context of transforming one's self-concept from an egocentric to a more transpersonal one, we can argue that the contemplative training (of which the lifestyle is an integral part) likely influenced the kinds of between-group differences observed here. Future studies could use first-person investigation to supplement third-person methods of the kinds used here to better understand the role of self-selectivity bias, mental training, and lifestyle with somewhat greater clarity.

Another limitation is that while we observe neural differences in processing of pleasant and unpleasant self-views between groups, potentially reflecting different strategies and underlying processes for evaluating affective self-views, we did not 1) use a high-density EEG to give us more precise cortical sources for ascertaining anatomical differences and 2) conduct interviews to investigate if participants were aware of the strategies they were using to evaluate differences between valence.

To summarise, long-term meditators have self-reference processing styles characterised by behavioural and brain responses that are less maladaptive than controls. Such changes might be how long-term meditation training supports a more flexible and healthy relationship to one's self, and may be a critical factor mediating improvement in mood disorders following contemplative-training-based therapy programs.

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Open Practices Statement

The data for figures and statistical analyses scripts are available at https://osf.io/xq8vw/. The experiment was not pre-registered.

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Figure Captions

Figure 1. Percent of self-endorsed pleasant (black) and unpleasant (grey) adjectives for the two groups, long-term meditators and controls. Error-bars show standard errors of the means.

Figure 2. A) ERPs for pleasant (black lines) and unpleasant (grey lines) words presented during the SRET at medial frontal-central channels for long-term meditators (solid lines) and controls (dashed lines). B) P200 amplitudes within the leftmost shaded region in A (pleasant and unpleasant words as black and grey bars respectively). C) early LPP amplitudes within the middle shaded region. D) late LPP amplitudes within the right shaded region.

Figure 3. Topography of the A) early-LPP interaction effect, and the difference between pleasant and unpleasant words in the B) meditator, and C) control groups (stars indicate channels with $p < 0.1$, FDR corrected).

Figure 4. Fit to a generalised linear mixed model showing the relationship between self-endorsement for pleasant (black) and unpleasant (grey) adjectives, and early-LPP for long-term meditators (solid lines) and controls (dashed lines). Dots indicate individual participants. ***$p < 0.001$.

Figure 5. Time-frequency plots of A) the difference in power between pleasant and unpleasant words in controls, B) the difference between pleasant and unpleasant words in

meditators, C) the difference between A and B. Time on the axis is from the onset of the words. The outlines encompass significant clusters ($p < 0.05$).

Figure 1 (colour). Percent of self-endorsed pleasant (blue) and unpleasant (red) words for the two groups, long-term meditators and controls. Error-bars show standard errors of the means.

Figure 2 (colour). A) ERPs for pleasant (blue lines) and unpleasant (red lines) words presented during the SRET at medial frontal-central channels for long-term meditators (solid lines) and controls (dashed lines). B) P200 amplitudes within the magenta shaded region in A (pleasant and unpleasant words as blue and red bars respectively). C) early LPP amplitudes within the green shaded region. D) late LPP amplitudes within the orange shaded region.

Figure 3 (colour). Topography of the A) early-LPP interaction effect, and the difference between pleasant and unpleasant words in the B) long-term meditator, and C) control groups (stars indicate channels with $p < 0.1$, FDR corrected).

Figure 4 (colour). Fit to a generalised linear mixed model showing the relationship between self-endorsement for pleasant (blue) and unpleasant (red) adjectives, and early-LPP for long-term meditators (solid lines) and controls (dashed lines). Dots indicate individual participants. ***$p < 0.001$.

Figure 5 (colour). Time-frequency plots of A) the difference in power between pleasant and unpleasant words in controls, B) the difference between pleasant and unpleasant words in meditators, C) the difference between A and B. Time on the axis is from the onset of the words. The outlines encompass significant clusters ($p < 0.05$).

Supplementary Figure 1. Word-by-word endorsements by the two groups (meditators: blue, controls: red) for pleasant and unpleasant adjectives. Each bar represents the proportion of individuals within that group who self-endorsed the respective word.