**Alpha and theta oscillations are inversely related
to progressive levels of meditation depth**

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Abstract

Meditation training is proposed to enhance mental wellbeing by modulating neural activity, particularly alpha and theta brain oscillations, and autonomic activity. Though such enhancement also depends on the quality of meditation, little is known about how these neural and physiological changes relate to meditation quality.

One model characterises meditation quality as five increasing levels of “depth”: *hindrances*, *relaxation*, *concentration*, *transpersonal qualities* and *nonduality*. We investigated the neural oscillatory (theta, alpha, beta, gamma) and physiological (respiration-rate, heart-rate, heart-rate variability) correlates of self-reported meditation depth in long-term meditators (LTM) and meditation-naïve controls (CTL). To determine the neural and physiological correlates of meditation depth, we modelled the change in slope of the relationship between self-reported experiential degree at each of the five depth-levels, and the multiple neural and physiological measures.

CTLs reported experiencing more *hindrances* than LTMs, while LTMs reported more *transpersonal qualities* and *nonduality* compared to CTLs, confirming the experiential manipulation of meditation depth. We found that in both groups, theta (4–6 Hz) and alpha (7–13 Hz) oscillations were related to meditation depth in a precisely opposite manner. Theta amplitude positively correlated with *hindrances*, and increasingly negatively correlated with increasing meditation depth levels. Alpha amplitude negatively correlated with *hindrances*, and increasingly positively with increasing depth levels. The increase in the inverse association between theta and meditation depth occurred over different scalp locations in the two groups—frontal-midline in LTMs and frontal-lateral in CTLs—possibly

41 reflecting downregulation of two different aspects of executive processing—monitoring and
42 attention regulation, respectively—during deep meditation.

43 These results suggest a functional dissociation of the two classical neural signatures of
44 meditation training, namely, alpha and theta oscillations. Moreover, while essential for
45 overcoming *hindrances*, executive neural processing appears to be downregulated during
46 deeper meditation experiences.

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49 **Highlights**

50 ● Our study reveals neurophysiological changes that occur as meditation experiences
51 become deeper

52 ● Alpha and theta brainwaves are two reliable neurophysiological signatures of
53 meditation

54 ● Theta activity increased with more distractions, and was suppressed during deeper
55 experiences

56 ● Increased alpha activity was related to fewer distractions, and more deeper
57 meditation experiences

58 ● Deeper meditation experiences appear to involve a suppression of executive neural
59 processing

60

Introduction

Meditation training has been shown to improve executive functioning and mental health (Chiesa & Serretti, 2009; Leyland et al., 2019). These psychological changes are accompanied by reliable changes in brain (Cahn & Polich, 2006; Lomas et al., 2015) and autonomic (Jevning et al., 1992) activity. However, little is known about how these neural physiological changes are related to the quality or “depth” of meditation (Dunne et al., 2019; Lutz et al., 2007; Wallace, 1999). Such an understanding is essential for unravelling how meditation training impacts psychological well-being (Brown et al., 2007; Lutz et al., 2015).

The study of subjective experience during meditation requires overcoming reliability issues pertaining to introspective reports. This could be done through a Husserlian epoché-and-reduction approach to obtaining generic structures of subjective experience and correlating them with neurobiological measurements; a paradigm known as neurophenomenology (Varela, 1996). Or it could be done through a “front-loading” approach, where prior phenomenological insight about an experimental procedure is used to obtain experiential self-reports (Gallagher & Sørensen, 2006).

Berkovich-Ohana and colleagues used magnetoencephalography (MEG) to study brain correlates of “self-dissolution” during meditation using both a front-loaded paradigm (Dor-Ziderman et al., 2013) and a neurophenomenological approach (Dor-Ziderman et al., 2016). They found that heightened self-dissolution was related to decreased beta-band (13—25 Hz) activity in the parietal cortex. Another study periodically probed participants to determine whether they were “on task” or “mind-wandering” during focused attention meditation, and found an increase in alpha (7—13 Hz) and frontal midline theta (4—6 Hz) oscillations when

83 they reported being on task versus mind-wandering (Brandmeyer & Delorme, 2016). Their
84 findings support a large body of literature showing a reliable increase in alpha and theta
85 oscillations during meditation practice, irrespective of the type of meditation practiced or
86 amount of training (Cahn & Polich, 2006; Lomas et al., 2015). However, it was unclear how
87 these oscillations were related to the *way* meditators were on task, for example, effortfully or
88 effortlessly (Lutz et al., 2015). Effortful and effortless concentration during meditation was
89 examined in another study, which found that deactivation of gamma-band (30—50 Hz) EEG
90 activity in the posterior cingulate cortex corresponded to the experience of effortless
91 concentration in both trained and novice meditators (van Lutterveld et al., 2017). Current
92 evidence thus suggests that introspection-related brain activity during meditation can be
93 observed in theta, alpha, beta and gamma oscillatory frequency bands.

94 Beyond measuring meditation depth along specific experiential dimensions like self-
95 dissolution and effortless concentration, researchers have constructed a more general
96 classification system in which different experiences are grouped into levels of meditation
97 depth (Piron, 2001). Assessing advanced meditators from a variety of contemplative
98 traditions, Piron (2001) developed the Meditation Depth Questionnaire (MEDEQ) to probe
99 meditation quality independent of meditation tradition or type. The MEDEQ characterises
100 depth in five progressive levels. The first level, *hindrances*, includes challenges associated
101 with practicing meditation, such as drowsiness and distraction. The second level captures
102 experiences of *relaxation*. The third level captures experiences such as effortless
103 *concentration*. The fourth level, *transpersonal qualities*, captures interpersonal and positive
104 affect experiences, which occur more consistently at advanced stages of training. And the
105 fifth level characterises experiences of *nonduality* such as reduced subject-object distinction,

106 self-dissolution, which usually require extensive training to master (Josipovic, 2014; Piron,
107 2001). The MEDEQ thus provides a front-loading phenomenological instrument for
108 investigating the neurobiological substrates of meditation depth.

109 Meditation practice also alters autonomic activity, specifically, decreasing respiration
110 rate (RR) (Corby et al., 1978; Wielgosz et al., 2016) and increasing heart rate variability
111 (HRV) (Lehrer et al., 1999; Sarang & Telles, 2006; Tang et al., 2009). Additionally, decreased
112 heart rate (HR) has also been observed during meditation (Delmonte, 1985; Zeidan et al.,
113 2010), though practices engaging the affective system (e.g., compassion for others) are
114 accompanied by increased HR following long-term training (Lumma et al., 2015; Lutz et al.,
115 2009). Interoceptive signals play an important role in theories of conscious experience,
116 especially pertaining to self and affect (Damasio, 1999; Gallagher, 2006; Seth, 2013).
117 However, the relationship between autonomic signals and meditation experience is yet to be
118 carefully examined.

119 We investigated whether self-reported meditation depth was associated with seven
120 neuro-physiological measures (NPM); 4 neural oscillatory bands (theta, alpha, beta and
121 gamma), and 3 autonomic measures (RR, HR, and HRV) in long-term meditators (LTM) and
122 demographically-matched meditation-naïve control participants (CTL). To induce variability
123 in meditation depth, we administered an abbreviated version of the MEDEQ immediately
124 following four different conditions: listening to a story as baseline (BL), listening to chanting
125 (CH), and two different meditation practices (M1 and M2). For M1 and M2, the CTLs engaged
126 in *mindfulness of breath* and *loving-kindness meditation* practices widely used in mindfulness-
127 based interventions, and the LTMs engaged in their daily practices of *mantra concentration*
128 and *nonduality* (see Methods). Because the MEDEQ was developed to measure specific

129 subjective experiences during meditation practice irrespective of meditation type or
130 tradition, it allows us to combine or compare LTMs and CTLs despite implementation of
131 different meditation practices during M1 and M2.

132 We expected that, compared to CTLs, LTMs would experience greater meditation depth
133 (Hypothesis 1). Specifically, we expected fewer *hindrances* and greater *concentration*,
134 *transpersonal qualities*, and *nonduality* following M1 and M2 in LTMs versus CTLs, and
135 greater *relaxation* in both groups following CH, M1 and M2 versus BL. As introspection-
136 related brain activity has previously been observed in multiple frequency bands, including
137 theta, alpha, beta and gamma, our hypothesis for the neural correlates of meditation was
138 relatively broad and included all four of these bands. We expected that across participants
139 greater meditation depth would be positively associated with alpha, theta, gamma, and HRV,
140 and negatively associated with beta, RR, and HR (Hypothesis 2). Because meditation depth
141 was obtained in five levels, we measured this association as a change in slope across the five
142 depth levels in the correlation between self-reported ratings at a particular depth-level and
143 an NPM. A significant increase in slope across increasing depth-levels would indicate a
144 positive association and a decrease in slope would indicate negative association. Finally, it is
145 possible that the two groups use different neurobiological strategies to provide self-reports.
146 We therefore also expected that the association between NPMs and meditation depth would
147 be significantly different between groups (Hypothesis 2a).

148

Methods

Participants

We recruited LTMs ($n = 13$; 4 females; mean $\pm$ SD meditation training: 32.2 ± 9.7 years) and meditation-naïve CTLs ($n = 15$; 6 females). The groups did not differ significantly on age (LTM = 56.8 ± 12.3 ; CTL = 53.5 ± 14.2 years; Wilcoxon rank-sum test, $p = 0.83$) and years of formal education (LTM = 15.9 ± 3.0 ; CTL = 19.0 ± 1.2 ; $p = 0.08$). Participants reported no psychiatric or neurological diagnoses. All participants provided written informed consent in compliance with the Institutional Review Board of the University of California Davis.

EEG and physiological data acquisition

We used a 32-channel BrainVision ActiChamp system (Brain Products, Germany) to measure continuous EEG activity (sampling frequency 1000 Hz). The active ActiChamp electrodes help improve the signal-to-noise ratio. Each channel was ensured to have an impedance below 16 k Ω prior to data collection. We also measured continuous respiration and pulse (sampling frequency 128 Hz) using a respiration belt and a photoplethysmogram respectively through the NeXus-10 (Mind Media, Netherlands) device.

Procedure

Before beginning measurements, participants familiarised themselves with the MEDEQ questions to ensure they understood the meaning of each question. The participants first underwent a task measuring self-referential processing published elsewhere (Katyal et al., 2020). This was followed by four blocks (1) listening to a podcast story (baseline; BL; 9 minutes), (2) listening to chanting music (CH; 6 minutes), (3) meditation 1 (M1; 20 minutes),

171 and (4) meditation 2 (M2; 15 minutes). See Supplementary Materials for details about BL,
172 CH, M1 and M2.

173 ***Self-reported meditation depth***

174 We assessed self-reported meditation depth immediately after each block. To reduce
175 participant burden, we identified a subset of items (14 out of 30) that assessed each of the 5
176 depth-levels, specifically, MEDEQ items 2, 4, 6, 8, 10, 11, 12, 15, 19, 22, 23, 24, 26, 27 (Piron,
177 2001). We labeled the five depth-levels DL0 to DL4. Because *hindrances* are inversely related
178 to the other depth-levels, it was labelled DL0. The participants were required to rate each
179 item using a Likert scale from 0 (not at all), to 6 (medium) to 12 (maximum).

180 ***Statistical analyses***

181 We used linear mixed models (LMM) as implemented by the *lme4* package (version 1.1.21) in
182 R (Bates et al., 2014) for all analyses. The intercept for individual participants was used as
183 the random effect for all LMMs. Even though the self-reported meditation depth data was
184 based on a Likert scale, which is ordinal, using more than four levels (we used a 12-point
185 scale for each item of the MEDEQ) allows its treatment as continuous data (e.g., Johnson &
186 Creech, 1983; Norman, 2010). LMMs were examined to ensure they satisfied assumptions of
187 linearity, homoscedasticity, and normality of residuals. Interaction and main effects from the
188 LMMs were evaluated using type II Wald χ^2 tests through the *Anova* function in the *car*
189 package (version 3.0.2). Post-hoc differences were evaluated using *lsmeans* function, which

190 uses the Kenward-Roger method for estimating the degrees of freedom and performs a
191 multiple comparison correction using the Tukey method for a family of 4 estimates.

192 *Self-reported rating at each depth level*

193 Participants provided Likert-scale ratings for MEDEQ questions that loaded on each of the 5
194 depth levels (DL0—DL4). For Hypothesis 1, we investigated the 2-way interaction and main
195 effects of *block* (BL, CH, M1, M2) by *group* (LTM, CTL) on the ratings at each depth level.

196 *Association between meditation depth and neurophysiological measures*

197 For an NPM to be associated with meditation depth (Hypothesis 2), there would have to be a
198 significant change in the correlation between the NPM and self-reported rating across the 5
199 meditation depth levels. For example, if the strength of alpha oscillations is positively
200 associated with meditation depth, then the correlation between alpha and self-reported
201 rating across the 4 listening/meditation blocks would be low (or even negative) for DL0
202 (*hindrances*) and would significantly increase up to DL4 (*nonduality*). Such an effect can be
203 statistically determined as a 2-way interaction between alpha amplitude and depth-level (in
204 its 5 categorical levels, DL0 to DL4) when regressed upon the self-reported ratings, which
205 allows us to infer if the slope of the regression of alpha amplitude upon the ratings changes

206 significantly across the 5 levels of meditation depth. This kind of a mixed modelling approach
207 is akin to performing a repeated measures analysis of covariance.

208 Moreover, if a particular NPM was related to meditation depth differently between the
209 two groups (Hypothesis 2a), we would observe a 3-way interaction between that NPM,
210 depth-level and group when regressed upon self-reported ratings.

211 It is possible that some of the NPMs are correlated among themselves (Abdullah et al.,
212 2010) and their association with meditation depth may be mediated by another NPM. To
213 avoid this possibility and to obtain the NPMs that best independently predicted meditation
214 depth, we constructed a single multilinear mixed model where seven 3-way interactions
215 (NPM x depth-level x group), and seven 2-way interactions (NPM x depth-level) were
216 regressed upon self-reported ratings. For evaluating the 3- and 2-way interactions, their
217 dependent 2-way interactions (NPM x group and group x depth-level) and main effects (all
218 NPMs, group, depth-level) were also included in the model.

219 To obtain the NPMs that were significantly associated with meditation depth, we used a
220 stepwise top-down model reduction approach. For this, we first evaluated the full model
221 using maximum likelihood (ML) estimation (Zuur et al., 2009). Then in a stepwise manner,
222 we first reduced the 3-way interactions and then the 2-way interactions that did not
223 contribute significantly to the model. For model reduction, at each step we selected the
224 interaction with the lowest χ^2 value (based on a Type II Wald χ^2 test) and evaluated if it
225 contributed to the model significantly (alpha = 0.05; Bonferroni corrected for 14
226 comparisons, seven 2- and seven 3-way interactions each) using the likelihood ratio test in
227 the *anova* function in the R *stats* package (version 3.4.4). If the interaction did not contribute

significantly to the model, it was removed. When removing the 3-way interaction, we also removed its dependent 2-way interactions (i.e., NPM x group). Similarly, when removing a 2-way interaction, we also removed the corresponding main effect. This procedure was followed until only the significant interactions remained. We finally evaluated this reduced model with restricted maximum likelihood estimation (REML) to obtain accurate p -values (Zuur et al., 2009).

Post-hoc analysis consisted of evaluating the association between the significant NPM and self-reports at each depth-level separately. This was done using t -tests with Satterthwaite's method to estimate the degrees of freedom through the *summary* function of the *lmerTest* package (version 3.0.1). The p -values for the 5 depth-levels were multiple comparisons corrected using false discovery rate.

Results

Hypothesis 1: Self-reported ratings at different levels of meditation depth

Figure 1 shows ratings for the five depth levels of the MEDEQ for the two groups (LTMs, CTLs) and four blocks (BL, CH, M1, M2). We first tested for between-group differences in the five depth levels at BL as an indicator of trait differences. While there was a trend for LTMs to have fewer hindrances (DL0) than CTLs during BL ($t(26) = -1.95$; $p = 0.063$), none of the

Figure 1. Self-reports of meditation depth for the five depth-levels, **A)** Hindrances (DL0), **B)** Relaxation (DL1), **C)** Concentration (DL2), **D)** Transpersonal Qualities (DL3), and **E)** Nonduality (DL4). Each depth-level is plotted for the two groups Controls and Long-term Meditators and for four time-points, baseline (BL), chanting (CH), first meditation practice (M1) and second meditation practice (M2). The error bars indicate standard errors of the means. Significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.005$; **** $p < 0.001$.

246 other depth levels were different between groups (DL1: $t(26) = 0.41$; $p = 0.69$; DL2: $t(26) =$

247 1.28 ; $p = 0.21$; DL3: $t(26) = 1.41$; $p = 0.17$; DL4: $t(26) = -0.18$; $p = 0.86$).

248 Table 1 shows the interaction and main effects for the different depth-levels along with

249 the hypothesised post-hoc comparisons (post-hoc p -values adjusted using Tukey method for

250 a family of 4 estimates). For *hindrances* (DL0), there was a significant main effect of group,

251 with CTLs reporting significantly greater *hindrances* than the LTMs. For *relaxation* (DL1),

252 there was a significant effect of block, with significantly greater *relaxation* during M1

253 compared to BL. For *concentration* (DL2), there were significant main effects of block, with
 254 significantly greater reports of *concentration* for CH, M1 and M2 compared to BL, and group,
 255 with significantly greater *concentration* for LTMs compared to CTLs. For *transpersonal*
 256 *qualities* (DL3), there was a significant group by block interaction characterized by increased
 257 ratings of *transpersonal qualities* during CH, M1 and M2 compared to BL for the LTMs versus
 258 CTLs. For *nonduality* (DL4), there was a significant group by block interaction characterized
 259 by greater self-reports of *nonduality* for CH, M1 and M2 compared to BL for LTMs versus
 260 CTLs.

261 Table 1. Statistical effects for the linear mixed models corresponding to the 5 depth levels

Depth level	Interaction: group x block		Main effect: group		Main effect: block		Post-hoc comparisons
	$\chi^2(3)$	p	$\chi^2(1)$	p	$\chi^2(3)$	p	
Hindrances	0.43	0.94	6.68	0.010	6.67	0.083	CTL > LTM $t(78.38) = 2.81; p = 0.031$
Relaxation	1.86	0.60	3.23	0.073	10.35	0.016	M1 > BL $t(78.38) = 2.81; p = 0.031$
Concentration	2.14	0.55	5.86	0.016	24.36	<0.001	CH > BL $t(78.49) = 2.96; p = 0.021$ M1 > BL $t(78.66) = 4.48; p < 0.001$ M2 > BL $t(78.77) = 4.00; p < 0.001$
Transpersonal qualities	9.19	0.027					LTM: CH > BL $t(75.20) = 4.00; p < 0.001$ M1 > BL $t(75.20) = 4.36; p < 0.001$ M2 > BL $t(75.20) = 4.82; p < 0.001$ CTL: CH > BL $t(75.42) = 0.71; p = 0.89$ M1 > BL $t(75.63) = 0.86; p = 0.82$ M2 > BL

							$t(75.63) = 1.56; p = 0.41$
Nonduality	21.46	<0.001					LTM: CH > BL $t(75.10) = 5.25; p < 0.001$ M1 > BL $t(75.10) = 6.20; p < 0.001$ M2 > BL $t(75.10) = 6.24; p < 0.001$ CTL: CH > BL $t(75.32) = -0.01; p = 1.00$ M1 > BL $t(75.53) = 0.97; p = 0.77$ M2 > BL $t(75.53) = 1.23; p = 0.61$

262

263 **Hypothesis 2: Association between self-reports and neuro-physiology**

264 To evaluate which of the seven NPMs were associated with meditation depth across the five
265 categorical levels, we used a stepwise approach to model reduction for obtaining the
266 significant interactions between NPMs, depth-level and group, and between NPMs and
267 depth-level when regressed upon self-reported ratings (see Methods). A significant 3-way
268 interaction would indicate that slope of the regression of a particular NPM on self-reports
269 was different between depth levels and groups. A significant 2-way interaction would
270 indicate that slope of the regression of that NPM on self-reports was different between depth
271 levels (but not across groups). Figure 2A depicts the model-reduction process with columns

Figure 2. A) Stepwise model reduction. Columns show the steps and rows show the 3 and 2-way interactions modelled at that step. The square-root of the χ^2 value of the interaction is shown in shades of grey. Step 1 included all interactions. At each step the weakest interaction was dropped. The final reduced model revealed two significant 2-way interactions; depth-level x alpha and depth-level x theta. **B)** t values of the regression of alpha and theta upon self-reports at each depth-level. Filled triangles denote significant correlations ($p < 0.05$; FDR-corrected). Slopes of the regression fits for the linear mixed model at each individual depth level depicting how **C)** alpha and **D)** theta amplitudes (in μV) predict experiential self-reports.

showing steps and rows showing the 3- and 2-way interactions modelled at each step. At Step 1, all possible 3- and 2-way interactions for the seven NPMs were included (depicted in the leftmost column). In subsequent steps, the weakest non-statistically-significant ($p < 0.05$; Bonferroni corrected) 3-way interactions were dropped (starting from the lowermost row)

from the model, ultimately leading to no significant 3-way interactions. Then, starting from the weakest 2-way interaction all non-significant 2-way interactions were dropped. This procedure led to two significant 2-way interactions of depth-level with alpha ($\chi^2(4) = 68.23$, $p < 0.001$) and theta ($\chi^2(4) = 55.38$, $p < 0.001$) amplitude.

Next, we performed post-hoc t -tests to investigate how alpha and theta were related to self-reported ratings at each of the five depth-levels (Figure 2B). The relationship of alpha and theta with depth followed a strikingly complementary pattern. Alpha was significantly negatively correlated with *hindrances* ($t(81.00) = -4.20$, $p < 0.001$ (FDR adjusted)) and positively correlated with *transpersonal qualities* ($t(87.68) = 3.16$, $p = 0.009$) and *nonduality* ($t(75.17) = 2.88$, $p = 0.016$). Theta was significantly positively correlated with *hindrances* ($t(66.61) = 4.19$, $p < 0.001$) and negatively correlated with *transpersonal qualities* ($t(62.27) = -2.60$, $p = 0.045$).

Figures 2C and 2D show the estimated slopes of the relationship of self-reported ratings with alpha and theta at different depth levels, while Table 2 provides the statistical values for the pairwise comparisons of the slopes. Both for alpha and theta, the slopes were significantly different between DL1 and all other depth levels, with no significant differences between any other comparisons.

Table 2. Pairwise comparisons of the estimated slopes of the relationship between self-reported ratings at different depth levels (DL) and amplitude in the alpha and theta bands

DL comparison	Alpha			Theta		
	Estimate	$t(504)$	p	Estimate	$t(504)$	p

0 > 1	-23.70	-5.82	<.001	38.29	5.39	<.001
0 > 2	-22.11	-5.43	<.001	36.29	5.11	<.001
0 > 3	-29.02	-7.13	<.001	46.05	6.49	<.001
0 > 4	-28.20	-6.93	<.001	42.93	6.05	<.001
1 > 2	1.59	0.39	1.00	-2.00	-0.28	0.99
1 > 3	-5.33	-1.31	0.69	7.76	1.09	0.81
1 > 4	-4.50	-1.11	0.80	4.64	0.65	0.97
2 > 3	-6.91	-1.70	0.44	9.76	1.37	0.65
2 > 4	-6.09	-1.50	0.57	6.64	0.93	0.88
3 > 4	0.82	0.20	1.00	-3.12	-0.44	0.99

295

296 Figure 3 depicts brain topographies of the strength of the 2-way interactions of theta
297 and alpha with depth-level. Theta oscillation correlations were observed primarily over
298 medial and lateral prefrontal cortex and occipital cortex (Figure 3A; left). Alpha oscillation

correlations were also
observed over similar regions
in addition to the left parietal
cortex (Figure 3A; right).

We further tested
whether the association
between meditation depth
and alpha and theta was
present in both groups
separately (or driven by one
group). For this, we modelled
interactions of alpha and
theta with depth-level in the
two groups separately. The

two interactions were indeed
highly significant in both
LTMs (alpha: $\chi^2(4) = 17.30$, p
= 0.002; theta: $\chi^2(4) = 17.71$, p
= 0.001) and CTLs (alpha:
 $\chi^2(4) = 22.04$, $p < 0.001$; theta: $\chi^2(4) = 18.76$, $p < 0.001$).

Finally, we investigated if the two groups showed similar or different scalp
topographies of the interaction of the two frequency bands with depth level, as the latter may

Figure 3. Topographic plots of the relationship between theta (left) and alpha (right) amplitudes and meditation depth in the **A)** two groups combined, **B)** long-term meditators, and **C)** controls. Plotted are the square-root of the χ^2 values of the interaction effects between depth-level, and theta and alpha amplitude regressed upon self-reports. The values are signed by the direction of relationship, which was negative for theta and positive for alpha at all channels. Asterisks denote channels with significant interaction effects, thresholded for A) at Bonferroni-corrected $p < 2.5e-8$ and B—C) at Bonferroni-corrected $p < 0.025$.

321 indicate differences in cognitive processes involved in meditation depth or strategies used
322 for evaluating self-reported meditation depth. For the LTMs (Figure 3B), theta was related
323 negatively to meditation depth over medial frontal and occipital scalp locations, while alpha
324 was related positively to meditation depth over the same locations. For the CTLs (Figure 3C),
325 theta was negatively related to depth-level over left and right lateral frontal and central scalp
326 locations as well as occipital locations. Alpha was related to depth-level over medial and
327 bilateral frontal scalp locations along with occipital and left parietal locations.

328 ***Control analyses***

329 While the LTMs engaged in silent self-guided meditation, CTLs engaged in audio-guided
330 meditation. To ensure that differences in topographies between groups (particularly frontal
331 medial and lateral correlations with theta in the LTMs and CTLs respectively) were not
332 simply due to auditory stimulation, we also analysed the topographies using only the last 6
333 minutes of M1 and M2 during which participants were instructed to meditate in silence
334 (Supplementary Figure 1). These topographies were very similar to the topographies in
335 Figures 3B—C indicating that group differences could not be explained by differences in
336 auditory stimulation.

337 While M1 and M2 practices for CTLs are commonly used as part of mindfulness-based
338 interventions, CH is not. For applicability of our results to mindfulness-based interventions,

339 we also plotted the topographies by excluding the CH block (Supplementary Figure 2). These
340 topographies were again similar to when the CH block was included.

341 ***Exploratory analysis***

342 *Meditation depth during chanting*

343 The LTMs reported experiencing deeper meditation states even just through the brief
344 chanting intervention before beginning meditation. We explored if this deepening was
345 accompanied by brain mechanisms similar to meditation, specifically by a reduction in
346 frontal midline theta. Supplementary Figure 3 shows the theta topography for the LTMs of
347 CH compared to baseline, which again showed a locus at midline frontal regions though at a
348 somewhat lenient threshold ($p < 0.025$; uncorrected).

349 *Meditation depth and physiology*

350 Our planned analysis did not reveal a significant relationship between meditation depth and
351 the 3 physiological measures (HR, RR, HRV). It is however possible that if there were such a
352 relationship, it was being explained away by the neural correlations. We performed
353 exploratory analysis by regressing the 3- and 2-way interactions from only RR, HR and HRV
354 upon self-reports. Model reduction revealed three significant interactions. There was a 3-

way interaction of HR with depth-level and group ($\chi^2(4) = 13.48, p = 0.009$). Post-hoc comparisons revealed that this was because the change in slope across depth levels was different for the two groups (Figure 4A). While the slope increased for the LTMs, it decreased for the CTLs. When regressing HR on individual depth levels, we found a significant negative relationship between HR and DL3 for the CTLs (Figure 4B; $t(20.20) = -2.89, p = 0.045$), but no relationship between HR and any of the individual depth-levels was observed

in LTMs. There were also significant 2-way interactions of RR ($\chi^2(4) = 14.79, p = 0.005$) and HRV ($\chi^2(4) = 13.48, p = 0.009$) with depth level. For RR, the slope of its relationships with self-reports decreased with depth level, i.e., at greater depth levels there was a more negative

Figure 4. Slopes of regression fits for individual depth levels depicting how self-reported ratings are predicted by **A)** heart-rate (in cycles/minute) for the two groups, controls and long-term meditators, and **C)** respiration-rate (in cycles/minute) and **E)** heart-rate variability across groups. t values of the correlation between subjective reports of depth at each of the five depth-levels with **B)** heart-rate for the two groups, **D)** respiration-rate and **F)** heart-rate variability. Filled triangles denote significant correlations ($p < 0.05$; FDR-corrected) at that depth-level.

relationship between self-reports and RR (Figure 4C). Pairwise comparison revealed that the slope of RR at DL0 was significantly greater than for DL4 ($t(354) = 3.18, p = 0.014$). At individual depth-levels, RR was significantly (negatively) correlated to DL4 (Figure 4D; $t(86.00) = -3.42, p = 0.005$). The slopes of the relationship of HRV increased with depth level, i.e., at greater depth levels there was a more positive relationship between self-reports and HRV (Figure 4E). Pairwise comparisons revealed that slopes of HRV for DL0 were significantly smaller compared to DL1 ($t(354) = -3.41, p = 0.006$), DL3 ($t(354) = -3.74, p = 0.002$) and DL4 ($t(354) = -3.56, p = 0.004$). None of the correlations of HRV with individual depth levels survived FDR correction (Figure 4F).

Neural correlates of individual depth levels

For our planned analysis, we used a statistical approach that reveals the neural correlates that differentiate the different depth levels. Such an analysis approach however would miss neural correlates that are specific to a particular depth level (and do not change reliably across depth levels). Hence, as an exploratory analysis, we regressed the four neural measures (theta, alpha, beta, and gamma) and their interaction with *group* upon each of the five depth levels individually (Supplementary Figure 4). As above, we found that DL0 was significantly positively associated with theta ($\chi^2(1) = 17.52, p < 0.001$; $t(66) = 4.10$; $p < 0.001$) and negatively associated with alpha ($\chi^2(1) = 17.68, p < 0.001$; $t(80.5) = -4.10$; $p < 0.001$), with no interaction of either with group. DL1 and DL2 were not associated with any of the frequency bands. Again, as above, DL3 was significantly negatively associated with theta ($\chi^2(1) = 5.92, p = 0.015$; $t(77.9) = -2.38$; $p = 0.020$) and negatively associated with alpha ($\chi^2(1) = 14.65, p < 0.001$; $t(71.4) = 3.74$; $p < 0.001$), with no interaction of either with

group. DL3 was also significantly negatively associated with beta ($\chi^2(1) = 4.74, p = 0.029$; $t(44.2) = -2.13; p = 0.039$) and positively associated with gamma ($\chi^2(1) = 7.96, p = 0.005$; $t(67) = -2.77; p = 0.007$) with neither interacting with group. For DL4, we observed an interaction of the theta amplitude with group ($\chi^2(1) = 4.06, p = 0.044$). This interaction was due to a negative association between theta and DL4 only in the LTMs ($t(57.5) = -2.44; p = 0.018$; Supplementary Figure 4, DL4 Theta, grey line) and not CTLs ($t(42) = -0.17; p = 0.87$; black line). Finally, alpha was positively associated with DL4 ($\chi^2(4) = 7.52, p = 0.006$; $t(42) = 2.67; p = 0.009$)

Discussion

The goal of this study was to examine the relationship of the neural and physiological correlates of self-reported meditation depth in long-term meditators of the same contemplative tradition versus demographically-matched meditation-naïve adults. We expected that, compared to CTLs, LTMs would experience greater meditation depth (Hypothesis 1), and that across participants greater meditation depth would be positively associated with alpha, theta, gamma, and HRV, and negatively associated with beta, RR, and HR (Hypothesis 2).

We found evidence supporting Hypothesis 1. Compared to LTMs, the CTLs reported overall significantly more *hindrances* across all blocks (BL, M1 and M2). Both groups reported higher *relaxation* and *concentration* during meditation compared to baseline. The deepest experiences—*transpersonal qualities* and *nonduality*—were significantly heightened in the LTMs following M1 and M2 compared to BL, but not in the CTLs. Because the two

422 groups performed different meditation techniques, these differences may be due to either
423 the difference in the amount of meditation training between groups (several decades vs
424 none), or a difference in meditation practices themselves (for example, LTMs meditation
425 techniques involved an explicit component of meditative absorption, while the CTLs engaged
426 in guided focused attention on breath and then loving-kindness).

427 The self-reported meditation depth (MEDEQ) results suggest that even meditation-
428 naïve individuals can experience relaxation and concentration following the commonly
429 known mindfulness of breath, and loving-kindness meditation practices. They also indicate
430 that LTMs experience fewer hindrances such as distraction and drowsiness not only during
431 meditation, but also when performing a mundane task like listening to a podcast at baseline.
432 Moreover, while it was expected that LTMs (and not CTLs) would experience the deepest
433 levels of meditation experiences following meditation practices M1 and M2, we found that
434 LTMs reported experiencing these deepest levels also when listening to chanting at a level
435 comparable to M1 and M2. This suggests that regular training could enable deep meditation
436 experiences even through the practice of chanting. Our results indicate a need for better
437 understanding chanting practices in the future. Interestingly, we did not observe trait
438 differences during BL for any of the 5 depth levels. The lack of trait differences in the MEDEQ
439 may stem from the fact that it is a questionnaire that measures state modulations, and when
440 providing self-reports about experience, the absolute value that an individual provides as a
441 Likert rating would be expected to be normalised to their own (and not everyone's)
442 experience. Another reason for the lack of trait differences during baseline may be that
443 participants were actively engaged in the task of listening to a podcast. Previously, trait
444 differences between long-term meditators and novices have been mostly reported based on a

445 passive resting baseline (Cahn & Polich, 2006). We did not use a resting baseline because we
446 thought that during such a condition the meditators may habitually enter into a state of
447 meditation thus making it difficult to modulate meditation depth across blocks. We
448 recommend future studies to use both an active and resting baseline for measuring both
449 state and trait effects.

450 Hypothesis 2 was that meditation depth would be associated with one or more of the
451 seven NPMs, as determined by the change in the slope of the correlation between an NPM
452 and self-reported rating across the 5 depth levels. We found that meditation depth was
453 strongly associated with alpha and theta amplitude, respectively. While the relationship of
454 meditation depth with alpha was in the expected positive direction, its relationship with
455 theta was opposite to the expected direction. In fact, the two neural measures were
456 correlated to self-reported ratings across the 5 depth levels in a precisely opposite manner.
457 Theta correlated positively with *hindrances*, whereas alpha correlated negatively. At
458 progressively deeper levels, however, the self-reports became more positively correlated
459 with alpha and more negatively correlated with theta.

460 Hypothesis 2a was that the association between meditation depth and NPMs would be
461 different between LTMs vs CTLs. We did not find this to be the case. In fact, a similar
462 association of alpha and theta with meditation depth was strongly significant within each
463 group. This suggests that, despite the two groups engaging in different styles of meditation
464 practices and having vastly different amounts of meditation experience, change in self-
465 reported meditation depth relies on somewhat similar aspects of brain function. The lack of
466 group difference in our findings is also consistent with past studies that have found changes

467 in alpha and theta during meditation irrespective of the amount of meditation training or the
468 meditation tradition (Cahn & Polich, 2006; Lomas et al., 2015), and shown similar neural
469 correlates of effortless concentration between long-term meditators and novices (van
470 Lutterveld et al., 2017). Another reason we may not have observed group differences was
471 because of the way we conducted our planned analysis, namely, by associating NPMs with
472 self-reports across all 5 depth levels. Such an analysis disallowed measurement of group
473 differences at the deepest levels separately, which is where there may have been a difference
474 between groups. Indeed, post-hoc analysis revealed that the deepest meditation experiences
475 (*nonduality*) were negatively related with theta only in the LTMs and not in CTLs.

476 Alpha oscillations are closely linked to inhibitory processing and are often related to
477 suppression of distractors during attentional processing (Clayton et al., 2015; Jensen &
478 Mazaheri, 2010; Klimesch, 2012), whereas, theta oscillations (particularly frontal theta, as
479 we observed) are generally related to attentional monitoring, control or selection (Clayton et
480 al., 2015). As meditation deepens, we would expect greater suppression of distractors and
481 thus increased alpha. And, once the distractors have been suppressed during a deep state,
482 there would be less need for cognitive control due to a more effortless quality of
483 concentration, which may correspond to reduction in theta. In this sense, alpha and theta
484 might act in a complementary way with deepening meditation. This complementary
485 relationship was also evident in the similar set of brain regions where alpha and theta were
486 related to meditation depth—lateral and medial prefrontal, and occipital cortex.

487 While the association of depth with alpha and theta was present over the occipital
488 channels for both groups—indicating reduced visual sensory processing—there were group

489 differences in where these associations were centred over the frontal channels. Notably, the
490 association of greater meditation depth and lesser theta was present over medial-frontal
491 scalp locations in LTMs and lateral-frontal scalp locations in CTLs. Medial-frontal theta is a
492 classical signature of conflict monitoring and inhibitory control signals (Clayton et al., 2015;
493 Cohen, 2014). During meditation practice, such a cognitive process would be required, for
494 example, to monitor the contents of consciousness, and detect conflict if actual conscious
495 content (in the form of a distractor) does not match what one is expecting to meditate on.
496 Moreover, growing evidence suggests that lateral-frontal theta is related to attentional
497 regulation (Fellrath et al., 2016; Rajan et al., 2019; Spooner et al., 2020). From a cognitive
498 standpoint, conflict monitoring provides control signals for attention regulation (i.e., more
499 conflict triggers the need for more regulation) (Botvinick et al., 2001; Kerns et al., 2004),
500 which again would be required during meditation practice to upregulate the target and
501 downregulate distractors. It is thus possible that the different scalp locations of negative
502 correlations of meditation depth with theta oscillations were related to different aspects of
503 executive processes downregulated during deeper meditation. This would in turn imply that
504 trained meditators were able to downregulate executive processing at an earlier stage of
505 processing. While interesting from a mechanistic viewpoint, this interpretation remains
506 speculative in the absence of neural source localisation, and behavioural data. Moreover,
507 because the two groups were performing different practices during M1 and M2, it is unclear
508 if the differences in theta correlations were due to differences in the amount of training
509 (many years versus none) or the type of meditation techniques (deep absorption versus
510 mindfulness of breath/loving-kindness). In other words, the differences in topographies of
511 theta correlation in the LTMs vs. CTLs may have been due to the absorptive nature of

512 practices that LTMs engaged in. Though similar reduction in medial-frontal theta during a
513 response inhibition task in long-term meditators trained in practices (Vipassana) similar to
514 our control group suggests that our reduced medial-frontal theta may be a general feature of
515 prolonged meditation training (Andreu et al., 2019).

516 Although meditation depth was not related to psychophysiological measures when
517 modelled in combination with the neural measures, we did observe a relationship when
518 physiology was modelled separately. This indicates that neural activity in alpha and theta
519 bands effectively “explained away” variance of the physiological measures. Respiration-rate
520 was negatively correlated with the deepest (*nondual*) meditation experiences. This extends
521 previous anecdotal evidence of slowing down of respiration-rate accompanying deep
522 meditation experiences (Corby et al., 1978). In the LTMs moreover the baseline respiration
523 rate was negatively correlated with the amount of meditation training (Supplementary
524 Results), replicating a recent study (Wielgosz et al., 2016). We also observed that heart-rate
525 was negatively correlated with *transpersonal qualities* in CTLs but not LTMs. While
526 unexpected, this is an interesting observation with respect to theories that propose
527 subjective experience relies on predictive neural processing about interoceptive signals
528 (Gallagher, 2006; Seth, 2013). In this sense, heart-rate signals may have constituted the
529 evaluation of experience of *transpersonal qualities* in the CTLs but not LTMs, indicating that
530 long-term meditation training may reduce the influence of certain interoceptive signals as
531 somatic “markers” (Damasio, 1999) of subjective experience.

532 Finally, meditation depth was not related to beta and gamma oscillations, previously
533 associated with different subjective experiences during meditation (Dor-Ziderman et al.,

2016; van Lutterveld et al., 2017). We suspect two reasons for this. First, we used multivariate statistical models unlike previous studies that have correlated different frequency bands with self-reports using separate statistical tests for each band. The multivariate approach is advantageous because it enables a parsimonious discovery of correlates while accounting for covariation between them. Second, we measured the substrates of a relatively broad concept of meditation depth with 5 levels encompassing a larger variety of experiences including the previously studied ones. This enabled us to discover more general processes involved in deeper meditation compared to the specific processes investigated previously. Indeed, exploratory analysis at individual depth levels, which correspond to more specific experiences, revealed that beta and gamma amplitudes were negatively and positively related to *transpersonal qualities* respectively. The beta band negative correlation parallels the previously observed negative relationship between beta band activity and self-transcending experiences (Dor-Ziderman et al., 2013, 2016). The gamma band positive correlation however was in the opposite direction to the previously observed negative correlation between gamma band EEG activity and effortless concentration (van Lutterveld et al., 2017). There is growing evidence for the role of gamma-band activity in both trait- and state-based differences with meditation training (Braboszcz et al., 2017; Katyal & Goldin, 2021; Lutz et al., 2004). Functionally, gamma band activity has been related to conscious binding and attention (Engel & Singer, 2001; Jensen et al., 2007), which may have been involved in increased *transpersonal qualities*.

While the two groups performed different meditation practices (M1 and M2), the baseline and chanting blocks were similar for them. When comparing these two blocks between the two groups (Supplementary Results), we found that only the long-term

557 meditators had an increased gamma-band activity and increased heart-rate during chanting
558 compared to baseline, possibly indicating greater attention and arousal during chanting.
559 Interestingly, despite the increased heart-rate, there was a trend across both groups for
560 decrease in respiration rate from baseline to chanting, suggesting that the chanting practice
561 in long-term meditators may involve a simultaneous activation of the sympathetic and
562 parasympathetic system.

563 We administered the MEDEQ to assess participants' meditation experience after
564 relatively long meditation blocks (15–20 minutes). In contrast, some previous studies have
565 used experience sampling (Brandmeyer & Delorme, 2016) or online experience reporting
566 (van Lutterveld et al., 2017) methods. We used longer meditation blocks to allow
567 participants sufficient time to enter deeper levels of meditation without being distracted by
568 the need to introspect and report their experience. However, because accurate recollection of
569 experience is known to be difficult, our long blocks may have come at the cost of reliability of
570 recollection. To inform future studies about the meditation duration vs. depth trade off, we
571 examined the alpha and theta amplitude's correlation with meditation depth as a function of
572 duration from the beginning of the block over which we averaged the amplitude. We found
573 that in LTMs, significant correlation for both alpha and theta emerged around 8 minutes and
574 plateaued around 12 minutes from the beginning of blocks M1 and M2. Surprisingly, for the
575 CTLs, the correlation between meditation depth and alpha and theta emerged even as early
576 as 2 minutes into the meditation blocks. One possible reason for this difference in the
577 emergence of the correlation between groups could have been trait differences in deep
578 experiences between groups. For example, LTMs may have already started off at a deeper
579 experiential level at baseline, thus prolonging the difference in experiential depth to emerge

580 during meditation. CTLs, on the other hand, did not experience any depth at baseline and
581 thus entered states with fewer *hindrances* and more *relaxation* soon after meditation began.
582 Such an explanation would be supported by the trend for fewer *hindrances* in the LTMs
583 compared to CTLs during baseline. Another potential reason is that the experience of the
584 LTMs was progressing over the meditation period while the CTLs did not experience much
585 change in experience from the beginning.

586 One limitation of the present study is that the two groups engaged in different
587 meditation techniques. While the LTMs engaged in advanced absorptive practices, we used
588 more widely known mindfulness of breath and loving-kindness meditation practices for the
589 CTLs. As a result, the differences between groups in our Results could also be attributed to
590 the differences in the meditation techniques. One way this concern could be addressed in
591 future studies is by using guided absorptive meditation practices that are common for LTMs
592 and novices, and which are sufficiently close to the meditation techniques practiced by the
593 LTMs. Future studies could also have both groups doing both absorptive and
594 mindfulness/loving-kindness practices, as a better way to compare the different styles. A
595 second limitation is that by measuring neural correlations of the change in self-reports
596 within a participant, we were unable to measure the neural correlates of absolute level of
597 meditation depth. Measuring an absolute correlation of an experiential measure is
598 challenging because individuals can only report their experiences relative to themselves.
599 This could however be circumvented in future studies by using second person techniques,
600 where an interviewer uses phenomenological techniques to assess and rate a participant's
601 experience, which is then correlated with third-person (physiological) measures. Another

602 limitation is that we did not measure high-density EEG, and were thus unable to source-
603 localise the lateral prefrontal regions where theta was related to meditation depth.

604 To summarise, previous meta-analyses of neurophysiology literature on meditation
605 training have found alpha and theta oscillations to be the most reliable neurophysiological
606 signatures (Cahn & Polich, 2006; Lomas et al., 2015). However, until now no studies to our
607 knowledge have empirically differentiated the distinct roles played by these two frequency
608 bands in meditation. This is because previous studies did not take different levels of
609 meditation depth into account. By doing so, our results strongly indicate that while alpha
610 increases as meditation experiences deepen, theta decreases. Topographies of the
611 association of theta with meditation depth combined with their known functional cognitive
612 roles moreover indicates that meditation depth depends on reduced executive processing, at
613 the level of monitoring in the LTMs and at the level of control in the CTLs. Finally, as our
614 meditation-naïve control group engaged in mindfulness practices used in mindfulness-based

615 interventions for improving mental health and well-being in clinical and positive psychology
616 settings, our results are applicable to such scenarios.

617

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622

623 **Data Availability**

624 Study material, postprocessed data, and the R code for statistical analysis and generating
625 figures is available at osf.io/sfkte/. MATLAB code for the entire pre-processing pipeline is

626 available at github.com/sucharitk/meddepth. Full individual participant dataset will be
627 made available upon request.

628

629 Conflicts of Interest

630 None

631

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Figure Legends

Figure 1. Self-reports of meditation depth for the five depth-levels, **A)** Hindrances (DL0), **B)** Relaxation (DL1), **C)** Concentration (DL2), **D)** Transpersonal Qualities (DL3), and **E)** Nonduality (DL4). Each depth-level is plotted for the two groups Controls and Long-term Meditators and for four time-points, baseline (BL), chanting (CH), first meditation practice (M1) and second meditation practice (M2). The error bars indicate standard errors of the means. Significance levels: * $p < 0.05$; ** $p < 0.01$; $p < 0.005$; **** $p < 0.001$.

Figure 2. A) Stepwise model reduction. Columns show the steps and rows show the 3 and 2-way interactions modelled at that step. The square-root of the χ^2 value of the interaction is shown in shades of grey. Step 1 included all interactions. At each step the weakest interaction was dropped. The final reduced model revealed two significant 2-way interactions; depth-level $\times$ alpha and depth-level $\times$ theta. **B)** t values of the regression of alpha and theta upon self-reports at each depth-level. Filled triangles denote significant correlations ($p < 0.05$; FDR-corrected). Slopes of the regression fits for the linear mixed model at each individual depth level depicting how **C)** alpha and **D)** theta amplitudes (in μV) predict experiential self-reports.

Figure 3. Topographic plots of the relationship between theta (left) and alpha (right) amplitudes and meditation depth in the **A)** two groups combined, **B)** long-term meditators, and **C)** controls. Plotted are the square-root of the χ^2 values of the interaction effects between depth-level, and theta and alpha amplitude regressed upon self-reports. The

806 values are signed by the direction of relationship, which was negative for theta and positive
807 for alpha at all channels. Asterisks denote channels with significant interaction effects,
808 thresholded for A) at Bonferroni-corrected $p < 2.5e-8$ and B—C) at Bonferroni-corrected p
809 < 0.025 .

810

811 **Figure 4.** Slopes of regression fits for individual depth levels depicting how self-reported
812 ratings are predicted by **A)** heart-rate (in cycles/minute) for the two groups, controls and
813 long-term meditators, and **C)** respiration-rate (in cycles/minute) and **E)** heart-rate
814 variability across groups. t values of the correlation between subjective reports of depth at
815 each of the five depth-levels with **B)** heart-rate for the two groups, **D)** respiration-rate and
816 **F)** heart-rate variability. Filled triangles denote significant correlations ($p < 0.05$; FDR-
817 corrected) at that depth-level.

Supplementary Materials

Supplementary Methods

Participant recruitment

Sample-size justification

Our goal was to recruit highly-trained meditators with several decades' long meditation experience so that they were able to enter the deepest meditation experiences. Past studies investigating neural correlates of subjective experience during meditation have used sample sizes of expert meditators ranging from $n = 11$ (Dor-Ziderman et al., 2016) or 12 (Brandmeyer & Delorme, 2016; Dor-Ziderman et al., 2013) to $n = 16$ (van Lutterveld et al., 2017) reflecting the challenge associated with recruiting highly trained meditators. Of these studies, the one with the larger sample size recruited meditators with only an intermediate level of training (>5 years) as they investigated meditation experiences akin to an intermediate depth level (DL2). In order to measure experiences corresponding to DL3 and DL4, we expected to use more advanced meditators. We therefore aimed to recruit 12 or more long-term meditators in our study consistent with past work (Brandmeyer & Delorme, 2016; Dor-Ziderman et al., 2013, 2016).

Long-term meditators and their meditation tradition

LTMes were recruited from a single *Ananda Marga* meditation tradition through their regional and national email lists.

Ananda Marga (English translation: Path of Bliss; anandamarga.org) is a tradition of Tantra Yoga meditation originating in India and founded by Prabhat Rainjan Sarkar (also

known as Shrii Shrii Anandamurti). While Tantra Yoga meditation is believed to have been practiced in esoteric settings for several thousand years (Harper & Brown, 2002), Sarkar systematised these practices within a rational and pragmatic philosophical framework (Anandamurti, 1998; Taraka & Acyutananda Avadhuta, 2014) and made them universally available. An *Ananda Marga* practitioner is taught a fully codified sequence of six progressive meditation lessons by an ordained teacher (an *acharya*) over the span of several years. The teacher imparts each new meditation lesson to the meditator after ascertaining their progress on previous lessons. The six lessons themselves are part of the classical eight limbs of Yoga as codified by Patanjali in the Yoga Sutras (Anandamurti, 2010; Bharati, 2001). The first and sixth lessons are considered the main meditation lessons, and are the ones we asked the LTMs to practice in the present study (see the Meditation Blocks section below), while the four remaining are considered “helper” lessons. The first lesson involves concentrating with eyes closed on an internally visualised point of light while silently repeating a personal *mantra* (assigned by the instructor when first learning this practice), where the meaning of the *mantra* embodies the idea that one is dissolving their egocentrically-based feeling of self-consciousness (e.g., “I am someone”) into a transpersonal feeling of consciousness (“I am everything”). The sixth lesson is a “non-dual” meditation practice, which involves contemplating suspension of one’s intentional agency (e.g., “I am meditating”, or x is doing y) into a “transcendental consciousness” such that there remains a feeling of neither y nor x. The idea of transcendental consciousness in *Ananda Marga* philosophy (Anandamurti, 1998) has parallels to a Husserlian transcendental consciousness in that it evades any reflection at all (Hewitson, 2014) in contrast to the more widely-known idea of “pure consciousness” described in “Transcendental Meditation” literature, which has been previously investigated

866 using introspection (Travis & Pearson, 2000). Besides the first and sixth lessons, the other
867 lessons of meditation are supposed to help the meditator cultivate better single-pointed
868 sustained focus on the object of meditation (*dharana*), allow control over one's breathing and
869 as a result the parasympathetic nervous system (*pranayama*), and provide visualisation tools
870 for withdrawing attention from external senses to enable better concentration on the
871 meditated object (*pratyahara*). Besides these six lessons, Ananda Marga meditators are also
872 encouraged to follow moral guidelines codified in the Yogic system of *yama* and *niyama*, as
873 well as practice yoga postures (*asanas*) to cultivate a healthy body and mind (Taraka &
874 Acyutananda Avadhuta, 2014). The overall goal of *Ananda Marga* meditation practices as
875 stated in their motto is twofold: 1) at a personal level, to attain deeper levels of meditative
876 trance (*samadhi*), which in turn lead to a gradually better intuition about the nature of one's
877 consciousness, and 2) to dedicate one's life work for social and ecological welfare.
878 One reason for choosing this meditation tradition was that an older study from this tradition
879 reported a practitioner entering a deep state of meditative trance (*samadhi*) during the
880 study, but no follow-up investigation on this type of meditation practice has been conducted
881 since (Corby et al., 1978). A second reason was that because all meditation practitioners did
882 similar and well-specified practices in the same sequence, we can make stronger inferences
883 regarding what the neural correlates in the LTMs may reflect. LTMs were included based on
884 >10 years of regular daily meditation practice. Eight of the thirteen LTMs were ordained
885 monastics. LTMs reported engaging in multiple practices as part of their daily regimen,
886 which included 2—3 hours of daily sitting meditation.

887 *Control participants*

888 CTLs were recruited through online forums and by posting fliers in public and university
889 libraries in the Central California area and were required to be meditation-naïve.

890 **Missing data**

891 Due to technical difficulties, we did not obtain pulse and respiration measures for one of the
892 CTLs. On another CTL, measurement of pulse could not be distinguished from noise, so was
893 excluded. On one LTM, pulse measurement was excluded for the M2 block where it was
894 indistinguishable from noise. For the MEDEQ, only 3 (out of 112 total possible post-block
895 assessments) were missing across all participants.

896 **Meditation blocks**

897 For BL, participants kept their eyes closed and listened to a history-based podcast (*The*
898 *Memory Palace* Episode 36) narrating a brief biography of the child prodigy William J. Sidis
899 (thememorypalace.us/six-scenes-in-the-life-of-william-james-sidis-wonderful-boy). For CH,
900 with eyes closed participants listened to a musical chant (available online at: osf.io/sfkte)
901 involving a repetitive singing of a sanskrit mantra, *Baba Nam Kevalam*. LTMs were familiar
902 with this chant and could use this as a tool for meditation according to its meaning (“love is
903 the essence of everything”). CTLs were also told the meaning of the chant and asked to
904 simply listen to the music.

905 For M1 and M2, the LTMs engaged in two different self-guided meditation practices that
906 are part of their daily regimen (first and sixth lessons of *Ananda Marga* meditation; see
907 above). As these involve traditional elements like personalised *mantra* based on a process of
908 formal initiation into *Ananda Marga* meditation practices, and esoteric concepts like merging
909 one’s consciousness into an extended transpersonal consciousness, we could not use the
910 same practices with CTLs. Instead, we used more commonly known meditation practices for

the CTLs. For M1 in CTLs, we chose a focused attention on breath mindfulness meditation practice (by Tara Brach from tarabrach.com). We chose this practice because we thought it would overlap with M1 in LTMs in cognitive processing terms at least partly because of the instruction to try to retain focused attention on a mental object. A second reason for choosing this practice was that we expected to manipulate DL1 (relaxation) and DL2 (concentration) ratings in the CTLs through this practice and thus be able to measure their neurophysiological correlates in the CTLs. We did not expect that the CTLs could be instructed into the kind of non-dual absorption that LTMs engaged for M2. Instead, for M2 in CTLs we chose the meditation practice of loving-kindness towards a stranger, a close other, and oneself (by Elisha Goldstein from elishagoldstein.com), which we expected would manipulate DL3 (transpersonal qualities) in the CTLs. Meditation instructions for these audio-guided meditation practices in CTLs were delivered through headphones.

Because the MEDEQ measures subjective experiences independent of the type of meditation practiced, it allows us to combine or compare the two groups despite differences in M1 and M2.

EEG and physiology preprocessing

We used EEGLAB (Delorme & Makeig, 2004) and customized MATLAB code to conduct EEG data analysis. Raw EEG data were first downsampled to 250 Hz then band-pass filtered between 0.1–80 Hz, notch filtered with a 1 Hz bandwidth to exclude electrical line noise at 60 Hz, and re-referenced to the average of all electrodes. We then used Independent Component Analysis (ICA; as implemented in EEGLAB) to remove ocular and muscular artifacts (Delorme et al., 2007). Despite ICA, however, the four peripheral-most lateral channels (FT9, FT10,

933 TP9, TP10) still appeared to be contaminated with muscle artifacts in many subjects.
934 Moreover, midway through the study, the lead of one of the front-polar channels (FP2) was
935 corrupted. Accordingly, for the final analysis we excluded a total of six channels (FT9, FT10,
936 TP9, TP10, FP1, FP2). Results were however very similar when these channels were included
937 in analysis.

938 To compute the seven neuro-physiological measures, we first split each of the four
939 measurement periods, BL, CH, M1 and M2 into multiple 60-sec epochs with a 40-sec overlap
940 between adjacent epochs. Overlapping windows were used to ensure that we did not miss
941 any cycles of the physiological variables, which modulate at relatively low frequencies, at the
942 window edges. As M1 was 20 minutes and M2 was 15 minutes, we used only the last 15
943 minutes of M1 to match the duration of M2. We used the entire duration of BL and CH for
944 analysis. We then calculated the average amplitude in four frequency bands corresponding to
945 *theta* (4–7 Hz), *alpha* (7–13 Hz), *beta* (15–25 Hz), *gamma* (30–50 Hz) oscillations at each
946 channel using MATLAB's FFT function and then averaged these measures across all epochs
947 and all channels per block. Respiration-rate (RR), heart-rate (HR) and heart-rate variability
948 (HRV) were also calculated in similar 60-sec epochs. For calculating RR, we filtered the
949 respiration data between 0.04—0.4 Hz and calculated the median of the inverse time
950 difference between peaks corresponding to the inhale phase within each epoch. Epochs
951 where peak-duration differences were highly variable (interquartile range > 5) were marked
952 as artifactual and excluded from analysis; results were similar for a wide range of
953 interquartile range thresholds (e.g., $5 < \text{interquartile range} < 10$). Heart measures, HR and
954 HRV, were calculated in the 60-epochs using *HRVTool* toolbox (version 0.3) for MATLAB
955 (Vollmer, 2019), which provides a function to filter out artifactual pulses. HRV was calculated

956 in the high-frequency range (0.15–0.4 Hz) consistent with previous literature (e.g., Lumma et
957 al., 2015).

958 ***Statistical analyses***

959 *Association between amount of meditation training and neurophysiological measures*

960 We measured the amount of meditation training in years of training. To test the relationship
961 between the years of meditation training and NPMs during BL listening to podcast block, we
962 used a linear mixed model where we regressed each of the NPMs across the multiple 60-sec
963 epochs of the BL block on the duration of training with a random intercept for each
964 participant. Post-hoc analysis was conducted using the *emtrends* function of the *emmeans*
965 package, which calculates the degrees of freedom using the Kenward-Roger method.

966 ***MEDEQ questions used in our study***

- 967 1. I experienced equanimity and inner peace (DL 2)
- 968 2. My mind was constantly distracted by thoughts (DL 0)
- 969 3. The difference between subject and object disappeared (DL 4)
- 970 4. I gradually became more calm and patient (DL 1)
- 971 5. I could observe my thoughts from a distance (DL 2)
- 972 6. My mind was alert and clear (DL 2)
- 973 7. I felt sleepy and was dozing off (DL 0)
- 974 8. I felt love, surrender, connection (DL 3)
- 975 9. The feeling of time disappeared (DL 3)
- 976 10. I experienced a sense of boundless joy (DL 3)
- 977 11. My awareness expanded to an infinite space (DL 4)
- 978 12. I felt being accepted unconditionally (DL 3)
- 979 13. My mind was empty of thoughts, emotions and sensations (DL 4)
- 980 14. I experienced humility, grace, gratitude (DL 3)

981

982

Supplementary Figures

Supplementary Figure 1. Topographic plots of the relationship between theta (left) and alpha (right) amplitudes and meditation depth in **A)** long-term meditators, and **B)** controls for only the last 6 minutes of the meditation block. Plotted are the square-root of the χ^2 values of the interaction effects between depth-level, and theta and alpha amplitude regressed upon self-reports. The values are signed by the direction of relationship, which was negative for theta and positive for alpha at all channels. Channels with asterisks show significant interaction effects thresholded at Bonferroni-corrected $p < 0.025$.

985

Supplementary Figure 2. Topographic plots of the relationship between theta (left) and alpha (right) amplitudes and meditation depth in **A)** long-term meditators, and **B)** controls evaluated while excluding the chanting block. Channels with asterisks show significant interaction effects thresholded at Bonferroni-corrected $p < 0.025$.

986

987

Supplementary Figure 3. Topographic plots of the relationship between theta amplitude and meditation depth in long-term meditators for only the chanting block. Channels with asterisks show significant interaction effects thresholded at $p < 0.025$ (uncorrected).

988

989

Supplementary Figure 4. Linear mixed model regression estimates of the relationship between the four EEG frequency bands (theta, alpha, beta and gamma; depicted along the columns) and self-reported rating at the five depth levels (DL0–4; depicted along the rows). Error bars at the extreme values show the 95% confidence intervals. Only panels with either a significant interaction ($p < 0.05$) between the frequency band and group, or a significant main effect ($p < 0.05$) of the frequency band upon the self-reported ratings are shown. The interaction with group was significant only for theta at DL4 where the black line is for the CTLs and the grey line for the LTMs. The remain panels only had a main effect of the frequency band.

Results

Neural and physiological changes with amount of meditation training

We examined whether the duration of meditation training (in years) in the LTMs predicted any of the NPMs during BL. To do so, we regressed the number of years of practice upon the seven NPMs.

The amount of meditation training was not related to any of the four frequency bands (theta: $\chi^2(1) = 0.58, p = 0.45$; alpha: $\chi^2(1) = 0.02, p = 0.88$; beta: $\chi^2(1) \sim 0, p = 0.95$; gamma: $\chi^2(1) = 2.75, p = 0.10$) or heart-rate ($\chi^2(1) = 0.12, p = 0.73$). There was however a significant negative correlation between the amount of training and respiration rate ($\chi^2(1) = 7.61, p = 0.006$; $t(9.93) = -2.76, p = 0.020$; Supplementary Figure 5A).

We also evaluated the relationship between the amount of meditation training in the LTMs and the change in

Supplementary Figure 5. Linear mixed model regression estimates of the relationship between the amount of meditation training (in years) in the LTMs and A) respiration rate (cycles/min) showing a significant ($p = 0.020$) negative relationship between the two, B) change in theta amplitude (in μV) from BL to CH, M1 and M2 showing a significant ($p = 0.007$) positive relationship, and C) change in respiration rate from BL to CH, M1 and M2 showing a significant ($p = 0.040$) negative positive relationship.

1012 NPMs from BL to CH, M1, and M2. Such an analysis gives an idea of how meditation training
1013 may change the ability to manipulate the NPMs towards a particular experience. For this
1014 analysis, we regressed the amount of meditation training upon each of the NPMs over CH, M1
1015 and M2 after subtracting BL. We found a significant positive relationship between the
1016 amount of meditation training and change in theta ($\chi^2(1) = 10.90, p = 0.001; t(11) = 3.30, p =$
1017 0.007 ; Supplementary Figure 5B), and the amount of meditation training and change in
1018 respiration rate ($\chi^2(1) = 6.10, p = 0.014; t(7.68) = 2.47, p = 0.040$; Supplementary Figure 5C)
1019 but not alpha ($\chi^2(1) = 0.30, p = 0.58$), beta ($\chi^2(1) \sim 0, p = 0.96$), gamma ($\chi^2(1) = 0.48, p =$
1020 0.49), heart-rate ($\chi^2(1) = 2.37, p = 0.12$) and heart-rate variability ($\chi^2(1) = 0.15, p = 0.70$).
1021 Correlation plots of the regression estimates for theta (Supplementary Figure 5B) and
1022 respiration rate (Supplementary Figure 5C) revealed that it was not highly trained LTMs that

1023 increased these two NPMs over
 1024 meditation blocks compared to
 1025 BL, but rather the less trained
 1026 LTMs who decreased theta and
 1027 respiration rate compared to
 1028 BL.

1029 *Neural and physiological*
 1030 *differences between groups*

1031 Next, we performed exploratory
 1032 analysis on how the neural and
 1033 physiological measures differed
 1034 between the groups and blocks.

1035 Because the two groups
 1036 performed different meditation
 1037 techniques during M1 and M2,
 1038 we could not directly compare
 1039 the effect of expertise on these

1040 blocks. Instead, we compared
 1041 differences in NPMs between
 1042 groups for BL and CH. We again

1043 used linear mixed models and regressed the group-by-block interaction and main effects on

Supplementary Figure 6. Mean and standard errors of **A)** theta, **B)** alpha, **C)** beta, **D)** gamma amplitudes, and **E)** respiration rate, **F)** heart rate, and **G)** heart-rate variability for the two groups for the baseline and chanting blocks.

Supplementary Figure 7. Change in theta amplitude from BL to CH in **A)** LTMs and **B)** CTLs. **C)** Change in gamma amplitude from BL to CH in LTMs. Asterisks show scalp locations of channels that showed a significant difference $p < 0.05$ (Bonferroni-corrected for 26 channels).

the seven NPMs. Supplementary Table 1 provides the statistical values for the group-by-block comparison for seven NPMs, and Supplementary Figure 6 plots the changes in NPMs across groups and blocks.

There was a significant decrease in theta amplitude from BL to CH in both groups, which could be observed widely across the scalp

(Supplementary Figure 7A–B). There was also an increase in gamma amplitude from BL to CH specifically

in the LTMs, located over the right frontal and parietal channels (Supplementary Figure 7C). There was however no change in alpha or beta amplitude between the two groups and blocks. There was an increase in HR from BL to CH in the LTMs but not in the CTLs. There was also a trend across groups for a reduction in RR from BL to CH. Finally, HRV appeared to decrease from BL to CH in the CTLs but not in the LTMs.

Our analysis revealed no differences in BL between groups for any of the NPMs. Supplementary Table 1. Statistical effects for comparing how the seven NPMs differed between groups and blocks (BL and CH only)

NPM	Interaction:	Main effect:	Main effect:	Post-hoc comparisons
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	group x block		group		block		
	$\chi^2(1)$	p	$\chi^2(1)$	p	$\chi^2(1)$	p	
theta	0.71	0.40	0.01	0.91	38.93	<0.001	BL > CH $t(341) = 6.24; p < 0.001$
alpha	0.22	0.64	1.70	0.19	0.00	0.96	
beta	0.09	0.76	0.09	0.76	0.03	0.87	
gamma	4.27	0.039					LTM: CH > BL $t(340) = 3.10; p = 0.002$ CTL: CH > BL $t(340) = 0.29; p = 0.78$
respiration rate	2.16	0.14	0.68	0.41	3.30	0.069	BL > CH $t(249) = 1.81; p = 0.071$
heart rate	8.59	0.003					LTM: CH > BL $t(306) = 2.59; p = 0.010$ CTL: CH > BL $t(306) = -1.52; p = 0.13$
heart rate variability	2.99	0.084					LTM: BL > CH $t(198) = -0.45; p = 0.65$ CTL: BL > CH $t(190) = 2.11; p = 0.036$

1065

1066 *Neural correlation with meditation depth over time*

1067 We used relatively long periods of meditation (15–20 mins) to enable participants to

1068 sufficiently enter deep states of meditation. As an exploratory analysis, we also examined

1069 how the alpha and theta correlations with meditation depth changed as a function of the

1070 duration of the meditation period. Supplementary Figure 8 shows the *Chi*-squared values of

1071 the 2-way interactions alpha x depth-level and theta x depth-level when regressed upon self-

Supplementary Figure 8. Plot depicting how the association between meditation depth, and alpha and theta amplitude changed as a function of the time (in min) over which amplitude was calculated from the beginning of the meditation block separately for the two groups. Values plotted on the y-axis are the Chi-squared values of the interaction between depth-level, and alpha and theta amplitude when regressed using a linear mixed model upon self-reported ratings. Filled triangles are time points where the association was statistically significant ($p < 0.05$), while other points are shown by filled circles.

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