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Neural correlates of nonjudgmental perception induced through meditation

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Short title: *Neural correlates of nonjudgmental perception*

Graphical abstract:

Our results elucidate the neural mechanisms of a prolonged nonevaluative/nonjudgmental stance of perception. We found increased nonevaluative perception during binocular rivalry in long-term meditators following concentrative meditation. Increased nonevaluative perception was associated with the reduction in gamma-band phase synchrony in lateral-parietal and occipital regions.

Abstract

Ambiguous sensory stimuli provide insight into the dynamics of the human mind. When viewing substantially different images in the two eyes (i.e., binocular rivalry (BR)), perception spontaneously fluctuates between the two images along with patch-like mixtures of the two, with limited ability to control such fluctuations. Previous studies have shown that long-term meditation training can enable a more stable perception by reducing such fluctuations. Using electroencephalography (EEG), we investigated the neural bases of perceptual stabilization in long-term meditators (LTMs) and age-matched meditation-naïve control participants. We measured BR alternations before and after participants practiced meditation. We expected that perceptual stabilization through meditation could occur via one of two neurocognitive mechanisms: (1) a more engaged/effortful attention reflected by increased long-range phase synchronization between early visual sensory and higher-level brain regions; or (2) a disengaged/nonevaluative form of attention reflected by decreased phase synchronization. We found that compared with control participants, LTMs were in a significantly longer mixed perceptual state following concentrative meditation practice. The increase in mixed percepts across individuals was strongly correlated with reduced parieto-occipital gamma-band (30–50 Hz) phase synchrony. These findings suggest that concentrative meditation enables a nonevaluative perceptual stance supported by reduced communication between hierarchical visual brain regions.

Keywords: attention; perception; consciousness; meditation; binocular rivalry; EEG.

Introduction

Bistable visual stimuli, such as binocular rivalry (BR) or the Necker cube test, the limits of the visual perceptual system in being able to provide stable interpretations of incoming sensory information. This is because even though visual sensory stimulation is held constant, perception spontaneously fluctuates every few seconds between different possible interpretations of the sensory input. For example, during BR, individuals are shown conflicting images in the two eyes. Their perception, instead of being a fused combination of the two, typically fluctuates every few seconds between the two images (dominant percepts) interspersed with brief periods where the two images combine as a

“patchwork” (mixed percepts). Studies have shown that perceptual fluctuations during BR have little amenability to voluntary stabilization,¹ unless one specifically undergoes a rigorous training on such a task.² One exception to this is long-term meditation practitioners who can stabilize bistable perception through concentrative meditation.^{3–5} Here, we sought to investigate the neural mechanisms of such perceptual stabilization of BR through meditation.

Mechanistically, the stabilization of BR could occur in one of two ways. One, through heightened top-down control by increasing a low-level stimulus feature (e.g., contrast) to bias competition in favor of the perceived image.⁶ This would conform with classical views where heightened control is characterized by greater effort or engagement with a task.⁷ Alternatively, a different mechanism more consistent with phenomenological models of meditation might be at play. Here, instead of effortfully controlling mental fluctuations, one would do the opposite, namely, relinquish control by cognitively “defusing” from mental content⁸. Cognitive defusion refers to the process of refraining from conceptually evaluating/infering mental content (i.e., thoughts, sensations, memories, etc.) and is proposed to be a core process involved in meditation training. When considered within predictive coding models of rivalry, this strategy could also result in perceptual stabilization.^{9,10}

Predictive coding models of bistable perception typically involve a repeated comparison or evaluation of the current incoming sensory information against the expected internally represented probabilities of the different possible interpretations of the ambiguous sensory information.¹¹ The duration of a percept then depends on (1) the expected

probability of that interpretation (based on ecologically tuned parameters⁹), and (2) intrinsic neural noise for each cycle of evaluation. More evaluations would lead to a greater chance of perceptual switching due to noise. On the other hand, fewer evaluations would involve longer dwell times on the same percept.^{3,12} A nonevaluative strategy, moreover, would stabilize not only dominant perceptual states but also mixed percepts. This is because even though the probability of a mixed interpretation is considered low from an ecological viewpoint⁹, a reduced evaluation would reduce the chance to “fall out” of such a state to the higher-probability dominant state. Pagnoni (2019) moreover proposes that a nonevaluative meditative stance may also reduce the bias associated with the probabilities of the different rivaling interpretations.¹⁰ In this case, again, mixed percepts, which previously had lower relative probability compared with dominant percepts, would be expected to persist longer.

To our knowledge, these contrasting cognitive strategies—enhanced attentional control or a defused nonevaluative stance—have not been previously distinguished in terms of spontaneous EEG or magnetoencephalography (MEG) activity. However, the rivalry mechanisms described above and several lines of evidence suggest that the two strategies may be distinguishable in terms of communication between visual sensory and higher-order brain regions. Classical neural models of BR posit perceptual alternations as an outcome of hierarchical processing¹³ with a potential role for the lateral parietal and lateral prefrontal cortices in stabilizing rivalry in concert with the early visual cortex.^{14–16} Long-range phase synchronization has been proposed to be involved in communicating hierarchical information between sensory and higher-order regions, with gamma-band (>30 Hz) phase synchronization proposed to carry bottom-up (prediction error) and beta-

band (15–25 Hz) synchronization proposed to carry top-down (prediction) information.^{17–}

¹⁹ Both gamma- and beta-band long-range synchronization between lateral–prefrontal and lateral lateral–parietal and lateral lateral–parietal and occipital regions have been found to increase with a variety of executive cognitive tasks, including visual attention.^{20–23} Gamma-band synchrony between frontal, parietal, and occipital areas is also found to increase before BR transitions.^{24–26} LTMs have been found to exhibit higher lateral frontoparietal gamma synchronization during meditation compared with baseline,²⁷ potentially reflecting heightened attention during meditation.²⁸ On the other hand, a different kind of eyes-open meditation practice invoking a higher degree of attentional defusion⁸ was accompanied by the reduction in gamma-band synchronization across the brain.²⁹ Finally, long-range gamma synchrony has also been found to differentiate other strategic differences while viewing a bistable image, such as expected versus unexpected perceptual switching.³⁰ On the basis of this evidence, we reasoned that the degree of neural phase synchronization between two sets of brain regions—(1) lateral–parietal and occipital, and (2) lateral–frontal and lateral–parietal—would distinguish the two styles of attention. The more controlling/engaged style would involve increased phase synchronization, and the defused/disengaged would involve reduced phase synchronization (Fig. 1A). Thus, the degree of perceptual stabilization would be correlated positively to phase synchronization in the case of the former style and negatively for the latter. And this relationship may be observed in two frequency bands commonly associated with predictive perception—gamma and beta.^{17,19}

We recruited two groups of participants—LTMs and meditation-naïve controls (CTL) and examined EEG correlates of perceptual stabilization during BR. We expected that

dominance and mixed percept durations would be significantly longer in LTMs following meditation. Moreover, we expected a significant correlation between longer percept durations following meditation and gamma- and beta-band phase synchrony between channels over two sets of regions: lateral parietal–occipital and lateral frontal–lateral parietal. The direction of this correlation would reflect the neurocognitive mechanism underlying perceptual stabilization (Fig. 1A).

Materials and methods

Participants

We recruited fifteen (four females) LTMs from a single contemplative tradition (*mean* age = 56.8, SD = 12.3 years) where practitioners undergo rigorous training in concentrative practices (*mean* years of meditation training = 32.2, SD = 9.7) and fifteen (six females) CTLs matched for education and age (*mean* age = 53.5, SD = 14.2 years). Participants reported no history of psychiatric or neurological disorders and reported having normal or corrected-to-normal visual acuity. Participants provided written informed consent in compliance with the Institutional Review Board of the University of California Davis.

Recruitment process. LTMs were recruited from the local and national mailing lists of the *Ananda Marga* meditation community in the USA. Nine out of the 15 LTMs (two females) were ordained nuns and monks in the *Ananda Marga* (Sanskrit for Path of Bliss) contemplative tradition of Tantra Yoga. This tradition has a progressive specified path of daily training that includes moral behavioral guidelines (*yama* and *niyama*), concentration meditation on a point and verbal sound (i.e., *mantra*), subject–object nondual-absorption-

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3 style meditation (*dhyana*), physical yoga postures (*asanas*), and controlled breathing
4 (*pranayama*).³¹ LTMs reported practicing for at least 2 h for one or more decades. CTLs
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6 were recruited through online forums and fliers placed in public and university libraries.
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8 LTMs were included if they had greater than 10 years of regular practice (at least 1 h per
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10 day), although most reported meditating 2–3 h daily. On the basis of daily practice and
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12 retreats, we estimated that the practitioners had, on average, engaged in >40,000 h of
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14 meditation.
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22 *Stimuli*

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24 The BR stimuli were generated and administered via a computer using the Psychophysics
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26 toolbox (PTB-3)³² in MATLAB (The MathWorks Inc., MA) on a 53-cm monitor (60 Hz; HP
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28 ProDisplay P203; HP Inc., CA) kept at a distance of 74 cm from the participant. Participants
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30 viewed the rivalry stimuli through two 10-diopter prism glasses mounted on a wooden
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32 frame (Good-Lite Co., IL) and a cardboard platform. A black divider between the two eyes
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34 separated the delivery of stimuli to each eye.
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38 Stimuli were orthogonal grayscale gratings (orientations: $\pm 45^\circ$; Michelson contrast = 0.5
39
40 with luminance values between 0.25–0.75 for the monitor, where 0 is black and 1 is white;
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42 circular aperture with a viewing angle radius of 1.2°)³³ presented dichoptically through the
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44 prism glasses on the middle gray background (i.e., luminance 0.5). A fixation cross in the
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46 middle and a square box surrounding the gratings aided fusion of the aperture of the two
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48 eyes' stimuli.
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Procedure

Binocular rivalry. All participants were naïve to the BR paradigm. Upon arrival, participants underwent four 2-min practice runs. In the first two runs, participants were trained to view the stimuli through the prism glasses and press one of three buttons to report their perception: one for each of the two orthogonal gratings and one for a mixture of the two gratings. Participants were asked to report dominance if one or the other gratings filled >80% of the stimulus aperture and mixed otherwise and to press the button when their perception switched to a new state (either dominant or mixed). In two more practice runs, instruction to participants changed to what they would use during the actual study; they were asked to try, if possible, to maintain each of the three states of perception (two dominant and one mixed percepts) for as long as possible, while reporting their perceptual state. This instruction was used for all three of the experimental blocks of BR.

Before the BR study reported here, participants were administered a 6-min self-referential task published elsewhere.³⁴ Figure 1B shows the sequence of the task procedure. There were three separate blocks of BR (BR1, BR2, and BR3), with each block consisting of five 80-s rivalry runs (except the first participant who underwent four 140-s runs of BR per block). The three blocks of rivalry runs were preceded by (1) a baseline period (before BR1), where participants kept their eyes closed and listened to a 524-s podcast (<http://thememorypalace.us/>; Episode 36); (2) 1200-s eyes-closed meditation (before BR2); and (3) 900-s eyes-closed meditation (before BR3).

Meditation practices. Because LTMs were versed in specific practices prescribed by their meditation tradition as part of their daily routine, we ensured they engaged in those

practices before blocks BR2 and BR3. For the first meditation block (i.e., before BR2), LTMs focused with eyes closed on an internally visualized point accompanied by silently repeating and contemplating a Sanskrit phrase (mantra). This contemplation involved trying to merge one’s sense of being as an individually separate self-conscious into an all-encompassing consciousness. For the second meditation block (before BR3), LTMs tried to enter a state of “nondual” awareness that involves trying to suspend one’s individual intentional agency into an idea of a prereflective transcendental consciousness in a Husserlian phenomenological sense.^{35–37}

For the CTLs, who were naïve to meditation, we administered audio recordings of two more commonly known meditation practices through headphones. For the first meditation practice, they listened to a 20-min recording of focused attention on breath practice (<https://www.tarabrach.com/>) and were asked to follow the instructions. For the second meditation practice, they were asked to follow instructions from a 15-min recording of a “loving-kindness” practice (<https://elishagoldstein.com/>), which involved meditating on compassion toward a stranger, a close other, and themselves.

Though the two groups engaged in different sets of meditation practices, in both groups, the first meditation was more of a concentrative practice that begins with some degree of effortfulness and gradually leads to defusion, while the second involves a more sustained effortless defused state.

Participant exclusion

Four participants (two LTMs and two CTLs) were excluded from the analysis. Three of them had extreme dominance of one eye such that they did not report seeing any perceptual transitions to the other eye's image at all during one or more experimental runs. This prevented us from getting an accurate estimate of their average percept duration. One participant pressed the wrong buttons on the keyboard. Moreover, two LTMs showed outlying behavior in their dominant and mixed percept durations. One exhibited extremely long (>4 SD from the median) dominance durations during BR1, but not during BR2 and BR3, with a steep increase in mixed durations. Another participant reported extremely long mixed durations following BR1 and BR2. Follow-up interviews with these participants revealed that during BR2 and BR3, they experienced prolonged periods where images in two eyes separated (were not fused anymore) in addition to the more common patchwork-like mixed percepts. It was unclear if such separation was due to eye-convergence differences or a higher-level mechanism. We excluded the first participant from dominance duration analysis and both participants from mixed duration analysis. We also interviewed other participants after measurements, and they did not report any eye separation during the rivalry task.

EEG data acquisition

EEG data were acquired using a 32-channel BrainVision ActiChamp system (Brain Products, Germany) at a sampling frequency of 1000 Hz throughout the experiment. The ActiChamp system uses active electrodes that improve the signal-to-noise ratio at each electrode measuring location. All channels were ensured to have an impedance below 16

kΩ before beginning the experiment, though channels used for analysis in the present study had impedance below 5 kΩ.

Behavioral analysis

For each block of five BR runs in each participant, we took the median of all durations where participants reported continuous periods of exclusive dominance (+45° or -45° gratings) and the mixture of the two stimuli. Analyses were conducted separately on the dominant and mixed percept medians where BR2 and BR3 were compared with BR1.

EEG analysis

We used EEGLAB³⁸ and customized MATLAB code to conduct EEG data analysis. Raw data were first downsampled to 250 Hz then band-pass filtered between 0.1 and 80 Hz, notch filtered with a 1-Hz bandwidth to exclude electrical line noise at 60 Hz and rereferenced to the average of all electrodes. We then used Independent Component Analysis (ICA; as implemented in EEGLAB) to remove ocular and muscle artifacts.³⁹

Phase synchronization. Phase synchronization between channels was calculated during the rivalry blocks as the debiased weighted phase-lag index (*dwPLI*).⁴⁰ To calculate *dwPLI*, we first obtained the squared debiased weighted phase lag index (*sdwPLI*)⁴⁰ in the time domain.⁴¹ For this, we band-pass filtered the time series at each channel in the beta (15–25 Hz) and gamma (30–50 Hz) band using a zero-lag finite impulse response filter. We then obtained the phase $\Phi_{f,n,t}$ of the Hilbert-transformed time series for the two frequency bands (f) at each time point t and for each channel n . Instantaneous phase value at each time point was then subtracted for each channel pair (n_i, n_j):

$$\Delta\Phi_{f,n_i,n_j,t} = \Phi_{f,n_i,t} - \Phi_{f,n_j,t}$$

We then calculated the *sdwPLI* over a single run of BR as:⁴⁰

$$sdwPLI_{f,n_i,n_j} = \frac{(\sum_t \sin(\Delta\Phi_{f,n_i,n_j,t}))^2 - \sum_t \sin^2(\Delta\Phi_{f,n_i,n_j,t})}{(\sum_t |\sin(\Delta\Phi_{f,n_i,n_j,t})|)^2 - \sum_t \sin^2(\Delta\Phi_{f,n_i,n_j,t})}$$

In this equation, the left sides of the numerator and denominator correspond to the squared value of the weighted phase lag index, while the right sides contain coefficients used for debiasing. The intuition behind the left side is that it evaluates to a high value if one of the channels continuously leads or lags the other. Here, taking the sine of the phase difference helps reduce volume conduction effects by downweighing time points for which the two channels are in identical phase or in phase opposition. The intuition behind the debiasing coefficient is that it should decrease in value compared with the left side terms as the number of samples increase provided there is synchronization present, thus reducing bias associated with small sample sizes. This debiasing coefficient, however, can introduce negative values in the *sdwPLI*. Such a negative sign is not of physiological significance (e.g.,

directionality of connectivity). Following recent suggestions, we thus rounded the negative values to zero.⁴² We then took the square root of the *sdwPLI* to get the (unsquared) *dwPLI* and averaged it across runs within a block for each tested channel pair to get a value for each block (i.e., BR1, BR2, and BR3). When testing synchrony between multiple sets of channels, the *dwPLI* was averaged across those channels.

Experimental design and statistical analyses

Our study had a 3-block by 2-group mixed-effects design. For statistical quantification, we used mixed models implemented in R. The behavioral data (perceptual dominance and mixed durations) violated homoscedasticity assumption of linear models. We, therefore, used a generalized linear mixed model (GLMM) implemented by the *lme4* R package (version 1.1-21). For rivalry dominance durations, a GLMM with an inverse Gamma distribution provided the best fit, while for mixed durations, GLMM with a log-normal distribution provided the best fit. For all mixed models, we used two levels of the group (LTMs and controls) and three levels of the block (BR1, BR2, and BR3) as fixed effects and individual participants as a random effect.

The main and interaction effects for the mixed models were evaluated using type II Wald chi-square tests through the Anova function in the *car* package (version 3.0-2). Post-hoc multiple comparisons tests were performed using Tukey’s Honest Significant Difference (HSD) test, and differences were calculated between the least-squared means of each factor level using the *lsmeans* package (version 2.27-62).

The self-report questionnaire data were ordinal, and we expected the BR durations to contain some outliers. We, therefore, used the more robust, nonparametric Kendall τ - b , for evaluating correlations between brain and behavioral responses.

Results

Duration of dominant and mixed percepts in LTM versus CTL

We hypothesized a *group* by *block* interaction such that the LTMs would have longer dominant and/or mixed percept durations following one or both meditation periods (i.e., blocks BR2 and BR3) compared with baseline (BR1). We tested this hypothesis using GLMMs with the *group* and the *block* as fixed effects and a participant as a random effect (see Methods). Figure 2A and B show the median durations of reported dominant and mixed percepts, respectively, in the two *groups* (LTM and CTL) and across the three *blocks* (BR1, BR2, and BR3) after removing participants who reported breaking of binocular fusion/overlap of the two eyes' images (Fig. S1 plot durations with these participants included, online only).

For dominance durations, there was no *group* by *block* interaction ($\chi^2(2) = 0.72, P = 0.70$; type II Wald χ^2 test), or main effect of *block* ($\chi^2(2) = 2.92, P = 0.23$) or *group* ($\chi^2(1) = 0.31, P = 0.58$). For mixed durations, there was a significant *group* by *block* interaction ($\chi^2(2) = 10.79, P = 0.005$). Post-hoc comparisons revealed that for LTMs, mixed percept durations were significantly longer for BR2 versus BR1 ($z = -3.93; P = 0.003$) with a trend for BR2 to be greater than BR3 ($z = 2.32; P = 0.053$) in the LTMs (P values adjusted by the Tukey

method for comparing a family of three estimates). In the CTLs, we did not observe longer mixed percept durations for BR2 versus BR1 ($z = 0.36$; $P = 0.93$) or BR2 versus BR3 ($z = -1.30$; $P = 0.40$). Note that there is one CTL participant that could be considered a within group outlier (but is not an outlier when considering both groups together) who had longer mixed durations during BR1 compared with BR2 and BR3. Even after excluding this CTL participant, the increase in mixed percepts in the CTLs from BR1 to BR2 was not significant ($z = -1.66$; $P = 0.22$).

An earlier study on BR with LTMs reported stabilization of dominant percepts through an unconventional statistic, i.e., the percentage of participants whose rivalry durations increased following meditation.⁵ They reported that 50% of their participants perceived increased dominance durations following concentrative meditation. By comparison, we computed this statistic and found that 77% and 69% of our LTMs reported an increase in dominance durations during BR2 and BR3 compared with BR1, respectively. By contrast, 69% and 53% of the CTLs reported increased dominance for BR2 and BR3.

Correlation between neural phase synchronization and increase in mixed percepts

We hypothesized the stabilization of perception measured as increased mean percept duration would be correlated with long-range neural phase synchronization between EEG channels over two sets of regions: (1) lateral parietal and occipital (henceforth “parietal–occipital”), and (2) lateral frontal and lateral parietal (henceforth “frontal–parietal”). And over these two sets of regions phase synchronization could occur in two frequency bands, gamma and beta. As our predicted behavioral manipulation of longer durations was only

found for mixed percepts during BR2 versus BR1, we performed four correlations (two sets of regions $\times$ two frequency bands; Fig. 3). We measured phase synchrony using the debiased weighted phase lag index (*dwPLI*; see Methods) and calculated the correlation (Kendall τ) between change in mixed duration and *dwPLI* from BR1 to BR2. After correcting *p* values for multiple comparisons (Bonferroni correction across frequency bands and FDR correction across brain regions), we found a significant negative correlation between mixed percept duration and gamma-band synchronization over parietal–occipital regions ($\tau = -0.44$; $n = 24$; $P = 0.008$). There was however no significant correlation between mixed percept duration and gamma-band synchronization over frontal–parietal regions ($\tau = -0.23$; $n = 24$; $P = 0.12$), or beta-band synchronization over parietal–occipital regions ($\tau = -0.09$; $n = 24$; $P = 1$) and frontal–parietal regions ($\tau = 0.09$; $n = 24$; $P = 1$). Next, we calculated the correlation between change in mixed duration and parietal–occipital synchrony within each group separately. We observed a significant negative correlation for both the LTMs ($\tau = -0.49$; $n = 11$; $P = 0.040$) and CTLs ($\tau = -0.46$; $n = 13$; $P = 0.030$), indicating that the observed relationship was likely not driven by one or the other group.

Control analyses

Previous studies have shown an increase in gamma synchronization just before perceptual transitions.^{24–26} A negative correlation between gamma synchronization and mixed percept duration could, therefore, simply be an outcome of fewer perceptual transitions (rather than a defused attentional style). When excluding EEG data around the reported perceptual

transitions ([−500 +200] ms around a transition²⁴), we still observed a similar negative correlation between change in gamma synchrony and mixed percept durations ($\tau = -0.42$; $n = 24$; $P = 0.004$). At the same time, the correlation was not significant if gamma synchrony was calculated only around the transitions while excluding the nontransition period ($\tau = 0.05$; $n = 24$; $P = 0.75$). Because the perceptual transitions were reported by means of a motor response, this analysis also shows that the observed correlation was not due to motor influences on the EEG activity.

Long-range gamma synchronization has been proposed as a way to bind conscious visual perception across brain regions.⁴³ It is thus possible that the negative correlation between gamma synchronization and mixed duration may be due to reduced conscious binding during mixed perception compared with dominant percepts. On the other hand, if reduced synchronization is due to a defused attentional style, as we propose, then it should also be present when participants reported dominant percepts. By excluding sections of the EEG data during which the participants reported mixed percepts and only considering dominant perception, we still observed a significant (though expectedly somewhat weaker) negative correlation between gamma-band synchronization over lateral-parietal–occipital regions and change in mixed duration ($\tau = -0.29$; $n = 24$; $P = 0.049$).

Exploratory analyses

Supplementing our planned analysis in parietal–occipital and frontal–parietal regions, we explored the correlation between change in gamma synchrony and mixed percepts from BR1 to BR2 across the brain (excluding peripheral temporal and frontopolar channels

prone to muscular and ocular noise). Because no connections survived an FDR-corrected $P = 0.05$ for the possible 276 comparisons between the included 24 channels, we used a more liberal threshold of $P < 0.01$. We observed negative correlations (blue lines) for several lateral parietal and occipital connections (Fig. 4; blue lines). Interestingly, we also observed positive correlations for some right frontal to right parietal connections (green lines). These right-lateralized positive correlations were likely averaged away in our planned bilateral frontal–parietal correlations.

Discussion

Following concentrative meditation, LTMs perceived the BR stimulus as a mixture of the two images significantly longer than during baseline while the control group did not. While concentrative and mindfulness practices are considered to increase attentional control,²⁸ contemplative literature incorporating the first-person perspective suggests that attention is not improved in the way classical theories suggest.⁸ Even though the beginning stages of meditation practice (both within a session and over the course of long-term training) involve effortful concentration, the gradual reduction in mental distractions allows a meditator to concentrate with relatively more effortlessness and a “nonevaluative” or defused stance toward mental content. Our finding of prolonged ambiguous/mixed percepts during the BR block that followed the first meditation practice likely reflects such a nonevaluative stance of perception.

While we observed longer mixed percepts in the LTMs following the first meditation period compared with baseline, we did not find such a difference following the second meditation

period. This was unexpected, because if anything, we would have expected a greater stabilization of perception due to the potentially additive effect of the two meditation periods on mental stability. One reason this behavioral effect was observed only for the first and not the second meditation period could be that there is something unique about the defused state following a single-pointed concentrative style of practice, which was similar to the type of practice that induced rivalry stabilization in the original study.⁵ Another reason for not observing the effect after the second meditation period could have been participant fatigue, as they had already been part of the study for over 3.5 h, including EEG preparation, task orientation, and other tasks. Such a fatigue effect could have been mitigated had we counterbalanced the two meditation types. However, we decided against such a task design in order to ensure sufficient ability to detect a behavioral effect in at least one of the two meditation conditions. A third reason why we did not observe any difference for the second meditation could be due to a sequential order effect if, for example, rivalry naturally sped up over the course of a session due to a learning or adaptation mechanism.⁴⁴ Past work has shown that rivalry durations speed up when they are measured on different days,^{33,44} but remain fairly constant over different blocks in a session on the same day, so this explanation is less likely.

The change in mixed percept stability following concentrative meditation compared with the baseline state was correlated across individuals by the reduction in long-range gamma-band synchrony between lateral parietal and occipital cortices. The hierarchical relationship between the visual (occipital) and lateral parietal cortices is well known⁴⁵ with the two regions involved in low-level (early sensory) and higher-level (top-down regulatory) aspects of visual processing, respectively. With an increased attention, lateral

parietal and occipital regions are found to increase phase synchronization in the gamma band, indicating higher communication between the two.²³ The lateral parietal lobe is considered to be involved in the resolution and regulation of rivalry,^{15,16} with a stabilization of rivalry observed through stimulation of right lateral parietal regions.¹⁴ Long-range gamma-band desynchronization between parietal and occipital areas would, therefore, reflect reduced communication between sensory and attentional or regulatory aspects of visual perception. Through such desynchronization, our participants were able to let the ambiguous sensory stimuli be perceived as less resolved and more ambiguously. This supported the idea that a nonevaluative perception of the rivalry stimulus occurred through defusion, both cognitively and neurally. Moreover, because we observed a prolonging of only mixed and not dominant percepts, our findings could be more specifically considered as a state of toleration of perceptual ambiguity in the LTMs rather than a state of perceptual stability per se. A similar conclusion was reached in another recent study of perceptual bistability in the LTMs, where authors observed the presence of a frontal component of the event-related potential exclusively in the LTM (and not the CTL) group.⁴⁶ They interpreted the extra frontal processing in the LTMs as reflecting extra higher order/metacognitive processing that comes from being in a relatively defused state from the sensory stimulus, which is similar to our interpretation. Furthermore, their frontal component may have a functional link to the positive correlation between change in mixed percepts and gamma synchrony we observed over right frontal-parietal channels in our exploratory analysis as well.

Interestingly, the negative correlation between change in mixed percepts and lateral-parietal to occipital synchrony was significant even when only considering periods of

dominant percept and excluding mixed periods, indicating that the defused attentional style was likely present throughout the duration of the task. Moreover, the negative correlation between change in mixed percepts and parietal–occipital synchronization was statistically significant within both groups of participants. This indicates that some participants, even in the CTL group, may have experienced defused perception. This extends past work showing that even first-time meditators may be able to experience defusion following meditation,⁴⁷ albeit to a lesser degree compared with LTMs.

The correlation between neural phase synchronization and perceptual stabilization was observed only for the gamma and not the beta frequency band. According to predictive processing theories, this would indicate that disengaged perceptual stance was attained by disabling communication of bottom-up sensory information to higher-order regions. This finding is also consistent with previous work on attention where it was found that increased attention involves increased beta-band synchronization during a delay interval (i.e., while waiting for a stimulus to arrive) when there is need for more top-down regulation of sensory regions while gamma-band synchronization increases during the stimulus interval. And in our case, we also measured synchronization during the stimulus interval.

Our findings share some features with divided attention studies of BR.^{48,49} When simultaneously performing a second task, perceptual alternations of rivalry slow down. Our prolonged mixed percepts could be considered an outcome of the withdrawal of attention from the visual stimulus. However, our observations are different from the divided attention literature because, in our behavioral task, attention is not divided

between separate tasks involving two sensory modalities or a sensory and a cognitive modality like a thought or working memory. Hence, we reason for a nontask-directed defused attentional state.

BR alternations are known to slow down with age⁵⁰. Because our behavioral effect of longer mixed percepts in LTMs versus CTLs was observed despite the groups being matched in age, it is unlikely that the effect was due to age and more likely due to extensive meditation training. Moreover, a recent study found that slowing down of BR with age occurs exclusively for dominant and not mixed percepts,⁵¹ indicating that our findings are unlikely to be an outcome of participants' age group.

One limitation of our study is that in trying to disentangle the two types of perceptual styles, we did not obtain self-reports from the participants as to how they subjectively approached the rivalry task, as such phenomenological reports have been previously associated with differences in how participants approach a bistable perception task.³⁰

Another limitation is that by not using a high-density EEG with structural MRI on each participant, we were not able to source-localize the precise parietal and occipital regions underlying the gamma-band desynchronization related to perceptual stabilization.

To summarize, our results elucidate the neural mechanisms of a prolonged nonevaluative/nonjudgmental stance of perception. We found increased nonevaluative perception during BR in LTMs following concentrative meditation. Increased nonevaluative perception was associated with the reduction in gamma-band phase synchrony in lateral-parietal and occipital regions.

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Competing interests

The authors declare no competing interests.

Data availability statement

The code for statistical analysis and generating figures with fully processed data is available at osf.io/s8br9/. Full dataset and analysis code for data processing will be made available upon reasonable request.

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Figure captions

Figure 1. (A) The upper image shows baseline level synchronization between early visual and higher-order parietal brain regions. The lower images show the two potential mechanisms through which bistable perception may be stabilized through meditation. The lower-left image shows increased synchronization reflecting a more engaged style of attention while the lower-right image shows decreased synchronization reflecting a defused style of attention. (B) Task sequence: three five-run blocks of the binocular rivalry task (BR1, BR2, and BR3). BR1 was baseline and preceded by participants listening to a podcast. BR2 and BR3 were preceded by two separate types of meditation practices.

Figure 2. (A) Median dominance durations (seconds), and (B) median mixed durations, for the two groups (LTMs and CTLs) across the three blocks of binocular rivalry (BR1, BR2, and BR3). Box plots encompass the first and third quartile with the median indicated by the thick middle line. Whiskers extend to include all points barring outliers.

Figure 3. Scatterplot between the change in mixed percept durations and change in (A) parietal–occipital gamma (30–50 Hz), (B) frontal–parietal gamma, (C) parietal–occipital beta (15–25 Hz), and (D) frontal–parietal beta phase synchrony from BR1 to BR2. Shaded regions show 95% confidence intervals. Blue triangles show controls and red dots show long-term meditators. Nonparametric correlation coefficient calculated using Kendall τ -b.

Figure 4. Scalp view showing all long-range connections where there was a significant ($P < 0.01$; uncorrected) negative (blue lines) and positive (green lines) correlation between gamma-band synchrony and mixed percept durations.

Supporting information

Figure S1. (A) Median dominance durations, and (B) median mixed durations for the two groups (controls and long-term meditators) across the three blocks of binocular rivalry, including outliers.

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Figure 1. (A) The upper image shows baseline level synchronization between early visual and higher-order parietal brain regions. The lower images show the two potential mechanisms through which bistable perception may be stabilized through meditation. The lower-left image shows increased synchronization reflecting a more engaged style of attention while the lower-right image shows decreased synchronization reflecting a defused style of attention. (B) Task sequence: three five-run blocks of the binocular rivalry task (BR1, BR2, and BR3). BR1 was baseline and preceded by participants listening to a podcast. BR2 and BR3 were preceded by two separate types of meditation practices.

191x131mm (600 x 600 DPI)

Figure 2. (A) Median dominance durations (seconds), and (B) median mixed durations, for the two groups (LTMs and CTLs) across the three blocks of binocular rivalry (BR1, BR2, and BR3). Box plots encompass the first and third quartile with the median indicated by the thick middle line. Whiskers extend to include all points barring outliers.

88x157mm (600 x 600 DPI)

Figure 3. Scatterplot between the change in mixed percept durations and change in (A) parietal-occipital gamma (30–50 Hz), (B) frontal-parietal gamma, (C) parietal-occipital beta (15–25 Hz), and (D) frontal-parietal beta phase synchrony from BR1 to BR2. Shaded regions show 95% confidence intervals. Blue triangles show controls and red dots show long-term meditators. Nonparametric correlation coefficient calculated using Kendall τ -b.

177x152mm (600 x 600 DPI)

Figure 4. Scalp view showing all long-range connections where there was a significant ($P < 0.01$; uncorrected) negative (blue lines) and positive (green lines) correlation between gamma-band synchrony and mixed percept durations.

152x154mm (600 x 600 DPI)