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Spontaneous pupillary oscillations increase during mindfulness meditation

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A significant body of literature has shown that pupil size varies with cognitive and perceptual states [1,2]. Furthermore, the pupil diameter oscillates spontaneously at low frequencies, sometimes referred to as pupillary hippus [3,4]. Oscillation amplitude varies with many neural factors, including arousal and cortical excitability. Here we show that pupillary oscillations are modulated by mindfulness meditation, increasing by 53% compared to pre- and post-meditation baselines. The effect occurs only in trained meditators and is specific for low frequencies (below 1 Hz), with delta frequencies (1–5 Hz) unchanged. The study suggests that pupil size may be a useful marker of the altered cortical state during meditation.

We measured pupillary oscillations in a group of trained mindfulness-meditators before, during, and after a short period of meditation, with eyes open (see Supplemental Information for details of methods and example traces). Figure 1A shows the Fourier power of the dynamics of pupil size, averaged over all meditators, during baseline (average of before and after meditation: dark-grey trace) and meditation (red trace). The red trace clearly falls above the grey at low frequencies (<1 Hz, the hippus range), then becomes intertwined with baseline at higher frequencies (delta range).

Figure 1B shows average power in the low-frequency (Hippus) range before, during and after meditation. The meditation-induced effect was large and highly significant (Repeated measures Bayesian ANOVA: F(2,19) = 7.8, p = 0.001, log-BF = 1.38: strong evidence in favour). Hippus power measured during meditation was significantly higher than both baselines, before and after meditation (t(23) = −3.57, p = 0.002, log-BF = 1.36; t(19) = 3.63, p = 0.002, log-BF = 1.34, respectively), whereas there was no significant difference between the two baselines (t(19) = −0.68, p = 0.50, log-BF = −0.54). Conversely, average power in the adjacent Delta range (Figure 1D) was unaffected by meditation (ANOVA: F(2,19) = 2.0, p = 0.15, log-BF = −0.22).

To control that the effects were specific for meditation, we repeated the experiment with 20 participants who had never meditated, asking them simply to relax and listen to the meditation track. We found no significant change in Hippus in these participants (Figure 1C: Bayesian ANOVA: F(2,19) = 0.01, p = 0.99, log-BF = −0.87). Direct between-group comparison shows that the Hippus power change in meditators was significantly higher than in non-meditators (two-sample t(42) = 2.71, p < 0.01, log-BF = 0.61).

Figures 1E and F show individual results for meditators and non-meditators, plotting meditation-induced Hippus power change against pupil diameter change (both expressed as percentages of baseline values). For 20 of the 24 meditators the change in Hippus was positive. The increase (53%) is highly significant (t(23) = 4.14, p < 0.001, log-BF = 1.9, clear from the shaded 95% confidence limits shown as shaded blue regions. On the other hand, half of the 20 non-meditators showed a negative effect, and the average change was not significantly different from zero (t(19) = 1.05, p = 0.30, log-BF = −0.42). The abcissae of Figures 1E and F show the change of average pupil diameter compared with baseline. For both groups, the pupil constricted during ‘meditation’ by a similar amount (~7% in meditators: t(23) = −4.23, p = 0.001, log-BF = 1.98; ~4% in controls: t(19) = −3.42, p = 0.003, log-BF = 1.16; between group comparison: two-sample t(42) = 1.29, p = 0.203, log-BF = −0.45). Importantly, the pupil constriction did not correlate with the increase in Hippus power, for either group (mediators: r = −0.17, p = 0.4, log-BF = −0.7; controls: r = −0.20, p = 0.4, log-BF = −0.62). Furthermore, the constriction effect in meditators was driven only by the difference in the pre-meditation baseline (t(23) = 5.06, p < 0.001, log-BF = 2.79), probably due to dark-adaptation, with no significant difference between measurements during and after meditation (t(19) = −1.78, p = 0.091, log-BF = −0.06: Figure S1 in the Supplemental Information).

All the evidence suggests that the
meditation induces a generalized change in autonomic activity. It is possible that sympathetic and parasympathetic activity are driven by the dynamic balance between central nervous system and pupil diameter.

Lastly, we looked for correlations between the increase in Hippus power and cortical activity. In mice, where neural activity can be recorded directly, the changes in pupil oscillations and cortical activity are independent of, and therefore not driven by, changes in average pupil diameter.

Meditation may serve as a useful experimental procedure to manipulate cortical states in order to study the neural mechanisms driving spontaneous pupillary oscillations, and investigate how these relate to EEG, heart-rate, breathing and other major physiological parameters.

**SUPPLEMENTAL INFORMATION**

Supplemental Information includes experimental procedures, supplemental results, supplemental discussion, one figure and one table and can be found with this article online at https://doi.org/10.1016/j.cub.2020.07.064.

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