Working Paper
EEG Power and Coherence Analysis of an Expert Meditator in the Eight Jhanas[1],[2]

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Abstract: We report the first EEG recordings of an expert in the 8 advanced meditations called jhanas, and propose 5 hypotheses on how the jhanas differ in EEG power from the eyes-closed resting state at 7 different brain regions. We hypothesize simple changes in the brain regions responsible for each of the 5 principal experiential features of jhana states. These features are: (1) internal verbalizations fade, (2) external awareness dims, (3) the sense of personal boundaries is altered, (4) the experience of evaluations, goals, and "shoulds" diminishes, and (5) attention is highly focused on the object of meditation. The results strongly confirm reduced activity in the brain regions related to the first 3 hypotheses, with all 16 of the planned comparisons significant and in the predicted direction. With respect to Hypothesis 4, results are mixed, with all 4 predictions significantly confirmed in the alpha1 band, but all 4 disconfirmed in the theta band. Lastly, Hypothesis 5 was mostly confirmed, with 5 of the 6 planned comparisons in the predicted direction. The EEG spectra show strong, significant, and consistent differences in specific brain regions when the meditator is in a jhana state compared to normal resting consciousness.

Brain studies of expert meditators while in "peak states" have become increasingly sophisticated and better controlled. Lutz et al. (2004) reported high-amplitude gamma synchrony that was only present for 8 expert Tibetan Buddhists during compassion meditation and that was not exhibited by novice meditators. Brefczynski-Lewis et al. (2007) used fMRI to show that expert meditators activated a network of brain regions typically involved in sustained attention during concentrative meditation in a way that differed from novices. A SPECT study by Newberg et al. (2001) showed a unique decline in activity in the orientation center (posterior superior parietal lobule, or PSPL), for Tibetan Buddhist monks and Franciscan nuns, during mystical feelings of union with the universe.

All of the published studies of meditation limit themselves to one type of meditation (e.g., only metta or only Transcendental Meditation™). In contrast, some experts in Theravadan Buddhist tradition practice a set of 8 "jhana" meditations, each

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with different experiential qualities that may be discernable in brain studies. Though all 8 jhanas are Altered States of Consciousness (ASCs, reviewed by Vaitl et al. 2005), each jhana has different experiential qualities. The fact that a single subject can practice 8 different meditations allows a unique repeated measures analysis of brain states, where a single subject can act as their own control.

Phenomenal Experience of the Eight Jhanas

The experience of jhanas was reported frequently by the Buddha in many of his discourses (Nanamoli and Bodhi 1995), but the brain states of jhanas have never been studied. The practice of the 8 jhanas was preserved in the monasteries of the Theravadan tradition, but essentially disappeared in the Mahajana tradition (perhaps because it emphasized the "great vehicle," making Buddhist practices available to everyday people.) The most advanced description and training in the jhanas is given in the Visuddimagga ("The Path of Purification"), written in the 5th century.

The first jhana is described as intense physical energy and emotional joy, often accompanied by muscle tension, twitching, tears, hair standing on end, etc. The second jhana is more sedate, with physical relaxation, a strong sense of joy coming in waves and only a minor sense of physical energy. The third jhana is energetically quiet, but with strong contentment and happiness. In the fourth jhana the pleasure turns to neutrality, described as equanimity.

In the fifth jhana one senses an infinite space all around. In the sixth jhana one senses that one's consciousness has become infinite. In the seventh jhana there is a deep sense of nothingness, an absence of form. The eighth jhana is named "neither perception nor non-perception" because the mind does not even categorize the experience.

These eight jhanas are accessed through another ASC called Access Concentration (AC). In AC one is deeply concentrated on the object of meditation (often the breath), with little or no internal verbalization, and with consistently absorbed interest in the raw experience of the object of meditation.

Though each of the eight jhanas has unique characteristics, they are all ASCs that have in common the following 6 experiential characteristics: (1) internal verbalizations fade completely or become "wispy", (2) external awareness dims and startle responses diminish, (3) one's sense of body boundaries and orientation in space are altered, (4) the experience of evaluations, goals, and "shoulds" diminishes, (5) attention is highly focused on the object of meditation, and (6) the normal sense of time falls away (as is common in many ASCs). Jhana is distinguished from some other ASCs because it does not include visual or auditory hallucinations (as in some organic disorders), nor does it include cross-sense synesthesias (such as "seeing" the bell ring or "feeling" a bird sing, as in some drug experiences).

Predicted Differences in Brain Regions during Jhanas

Neuroscience has shown that many brain regions specialize in particular cognitive functions, some of which are related to meditation (Newberg and Iverson 2003; Lutz et al. 2004; Brefczynski-Lewis et al. 2007). The six experiential characteristics of the jhanas listed above suggest that some of the associated brain regions may not be performing their normal functions for a waking state, which may be detectable via EEG recording through increased power in the theta and alpha1 bands (4-8 Hz). Specifically, we propose 5 hypotheses based on specialization of specific brain regions related to the unique properties of the jhanas.

H1: Jhanas should show increased power compared to the rest state in Broca's area (BA44,45) and in Wernike's area(BA39,40) in the theta and alpha1 bands. Because a primary characteristic of jhana is that internal verbalization fades, then the brain regions associated with speech should become dormant or idle, associated with alpha1 or theta waves.

H2: Jhanas should show increased power compared to the rest state in the visual (BA 17-19) and auditory (BA 41-42) processing areas in the theta and alpha1 bands. Because the second property of jhana is that external awareness dims, then the brain regions associated with vision and hearing should become less active.

H3: Jhanas should show increased power compared to the rest state in the PSPL parietal area(BA5) in the theta and alpha1 bands. Since the next property of jhana is that the normal sense of personal boundaries is altered, the orientation area of the brain should show changes from normal rest.

H4: Jhanas should show increased power compared to the rest state in the dorsolateral PFC (BA 9,46) in the theta and alpha1 bands. Since jhana is experienced as a state where fewer evaluation, goals, and "shoulds" are perceived, the brain area associated with evaluation and goal attainment may become idle

H5: Jhanas should show increased power compared to the rest state in the Anterior Cingulate Cortex(BA 32,33) in the beta and gamma bands. Because attention is highly focused on the object of meditation in the jhanas, we would expect high activity in the ACC, which regulates and monitors attention.

The last property experienced in jhana, that the normal sense of time falls away, is not testable via EEG recordings. The few brain areas that are associated with timing (the suprachiasmatic nucleus and the cerebellum) are too deeply buried below the cortex to generate signals detectable via scalp EEG.

It should be noted that two alternative hypotheses also exist and have some support in the literature: instead of a particular brain region itself going inactive as we propose, either the region's *input or its output* may be cut due to some inhibitory process.

Newberg and Iversen (2003) have formulated such a theory where two cerebral areas are involved in mystical experience: the left PSPL (bodily orientation area, whose inactivity can produce a sense of unity with all things), and the intention association area of the left prefrontal lobe (which makes the intention to reduce input to the orientation area). Their causal mechanism is "deafferentiation" of the orientation area from its normal *input* in the thalamus, due perhaps to inhibition of the gamma waves that have been shown to mediate long-distance intracortical communication.

Another alternative is that the particular brain region may be functioning normally, but that parts of the frontal lobe and ACC that monitor consciousness are simply inhibiting *output* from that region. Wager et al. (2004) present a theory in which the attention association area in the frontal cortex is modulated by the "higher order" attention area of the ACC using a top-down process. Of these 3 possible mechanisms, our hypotheses embody the simplest mechanism possible - that each brain region itself becomes inactive (and therefore evidences higher power in the theta and alpha1 bands.)

Methods

The subject is a long-term Buddhist practitioner (53 years old male, left-handed). At the time of recording he had 17 years of training consisting of about 6,000 hours of practice, and was trained in the Sri Lankan tradition of jhanas by Ven. Ayya Khema (1997; 1991; 2001) The length of training was estimated based on his daily practice and the time spent on meditative retreats, where one day of retreat was counted as 8 hours of sitting meditation.

He entered the jhanas in the classical sequence, starting with Access Concentration, progressing through J1, J2, J3 etc up to J8, then returned to the resting state sequentially through J7, J6 etc, back down to J1. Following the second J1, two resting states were recorded, and subsequently treated as replicates. A randomly selected sequence of states was not recorded because each jhana builds on the previous one, hence the classical sequence was used. This sequence had been extremely well practiced by our subject as it is the "standard" jhana practice. Consequently it was very familiar, making state identification easy for our subject. Each jhana state averaged about 120-sec, with about 30-sec between states.

For each jhana state, the subject signaled with a single mouse click when he had entered the state. He clicked the mouse twice when he was leaving the state, and clicked three times whenever he achieved a particularly good exemplar of the state. These mouse clicks were automatically entered onto a spare EEG channel, producing synchronized registration of his responses.

EEG Recordings and Protocol

EEG data were recorded in 2002 at the University of Washington. The EEG system used a 256-channel Geodesic Sensor Net (System v.2.0 from Electrical Geodesics, OR), sampled at 500 Hz, and referenced to the vertex (Cz). Sections of the recording showing eye movements or muscular artifacts were manually excluded from the study. A digital high pass filter was applied to the data at .4 Hz and a hardware low pass filter at 200 Hz. A 60 Hz notch filter was employed to remove 60 Hz line artifact. Six epochs of 4 seconds each were extracted from each of the 21 states (2 resting states and 19 jhana states).

Spectral Analysis

For each electrode and for each 4-s epoch, the power spectral distribution was computed by using Welch's method, which averages power values across sliding and overlapping 500-ms time windows. Spectral bands were defined to be consistent with previous research: theta band was from 4 to 6 Hz, alpha1 band from 6-8 Hz, alpha2 band from 8-10 Hz, alpha3 from 10-12.5 Hz, beta from 12.5 to 25 Hz, and gamma from 25 to 42 Hz. The last is consistent with Lutz et al. (2004) who analyzed only the gamma range. The first 3 bands are congruent with Aftanas et al. (2001) who analyze only those bands. However we did not perform the analysis of alpha dominant frequency to establish frequency band boundaries individually for our subject, as Aftanas et. al did,. although our band frequencies are close to theirs. All power estimates are reported as a ratio of the power in a selected band to total power from 4-42 Hz.

Results: Power Analysis

The data were first examined for outliers and missing data. There were no bad channels so spatial interpolation was not required. Though no missing data was found, all of the data for Jhana 1 are outliers, with putative gamma power at least 10 times the gamma power of other Jhanas and Rest. It is likely that much of the gamma was due to muscle tension. Hence Jhana 1 is excluded from most analyses because it was more than 4 standard deviations away from any other state. All data for remaining states were approximately normally distributed.

Differences between Jhanas 2-8 and the Rest State

Figure 1 gives a graphical overview of the contrast between Rest power and the mean of Jhanas 2-8 power. For each of the six frequency bands, the 256 electrode sites are plotted as boxes indicating the difference between Rest power and the mean power of Jhanas 2-8. Larger boxes indicate larger deviations from the null hypothesis that mean Jhana power equals Rest state power. Open boxes indicate that the ratio is smaller than one, so that power in Jhana is less than that in Rest. Filled boxes indicate the ratio is *greater* than one. Box widths are proportional to the log of the ratio of power for the mean of Jhanas 2-8 relative to the mean of Rest states. Power for each electrode for each epoch is measured relative to average power for the entire range of 4-42 Hz. For example, Figure 1 shows large power increases from Rest to Jhana in the central parietal region in the theta band, as well as in some lateral frontal regions. The same increases appear in the alpha1 band, but the difference in the parietal region disappears in alpha2 and alpha3.

Statistical tests for the planned comparisons are shown in Table 1 for each of the 5 hypotheses. Hypothesis 1-4 predict that power will be greater in jhanas compared to the rest state for the theta and alpha1 bands for the brain regions associated with internal verbalization, external sensory awareness, sense of body boundary, and goal-attainment. The results strongly confirm the first 3 hypotheses, with all 16 of the planned comparisons in Table 1 significant and in the predicted direction. With respect to Hypothesis 4, results are mixed, with all 4 predictions significantly confirmed in the alpha1 band, but all 4 disconfirmed in the theta band because power in the jhanas was significantly less than resting power in that band.

The last two columns of Table 1 show the planned comparisons for the last hypothesis, that power will be greater in jhanas compared to the rest state for the beta and gamma bands for the brain regions regulating attention (Anterior Cingulate Cortex). In the beta band, this hypothesis was confirmed in all three comparisons (two of them very significantly). In the gamma band, two of the three comparisons were in the expected direction. However, site FCz showed significantly higher gamma in the rest state than in jhana, contrary to predictions.

Results: Coherence Analysis

Discussion

We presented the first EEG recordings of a meditator in the 8 advanced meditations called jhanas, and proposed 5 hypotheses regarding how the jhanas differ in EEG power from the resting state in 7 different brain regions. Hypotheses 1-4 predict that power will be greater in jhanas compared to the rest state for the theta and alpha1 bands for the brain regions associated with internal verbalization, external sensory awareness, sense of personal boundaries, and goal-attainment. The results strongly confirm the first 3 hypotheses, with all 16 of the planned comparisons significant and in the predicted direction. With respect to Hypothesis 4, results are mixed, with all 4 predictions significantly confirmed in the alpha1 band, but all 4 disconfirmed in the theta band. Lastly, Hypothesis 5, that power will be greater in jhanas compared to rest state for the beta and gamma bands, was mostly confirmed, with 5 of the 6 planned comparisons in the predicted direction. Our results show strong, significant, and predictable differences in specific brain regions when the meditator was in jhana state compared to normal resting consciousness.

Limitations: Our results are clearly limited to the individual who was recorded. It remains to be seen whether other students trained in his lineage will exhibit brain states that replicate his. If other students exhibit similar brain states as captured by EEG, then it seems likely that we are detecting intrinsic properties of these states, which would permit the development of a theoretical model of these states. Further data collection and analysis may then disclose differentials between the individual jhana states, permitting a finer grained typology to be developed.

On the other hand, if other long term meditators in this tradition exhibit distinctly different brain states from those explored here, this would raise several interesting questions. One would be whether there are subtypes of meditators who experience similar states but with different EEG signatures. Another would be whether the verbal descriptions of these states are too imprecise to permit them to be distinguished effectively. The study of correlates between verbal descriptions and these exotic states appears to be a fertile area for investigation.

Implications: A more general question is how the 8 jhanas fit into the meditation states of other traditions, such as Transcendental Meditation™ or Vipassana. Is the brain state of TM similar to that of one of the Jhana states? Or is it substantially different? If different, it suggests that there may be a vast array of ASCs which we are only beginning to describe, depending on which brain centers are given awareness and which are inhibited from awareness. If there are a large number of possible ASCs, it is likely that only some would have survival value. For example, the state of mystical union with all beings might be helpful in encouraging cooperation with all people in the tribe, so that evolution may have selected certain of these ASCs to be more easily learned and retained.

Our results suggest that "meditation" is NOT a unitary phenomenon, but is probably comprised of many species, each with a different brain state. We have added a new species to the category, and have shown its average correlates with brain states as measured by EEG. The task remains to continue this exploration at higher levels of resolution within the 8 jhana states.

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Table 1. Planned comparisons on 5 hypotheses about how Jhanas differ from Resting brain states. The first four hypotheses predict higher power in theta and alpha1 bands, while the last predicts higher power in the beta and gamma bands. In each bracket, the first number is the mean power for Jhanas averaged over all epochs, and the second number is the mean power for Rest states averaged over all epochs. All F statistics are with degrees of freedom of (1,754).

Hypothesis	**Brain region involved (and EEG site)**	**Theta Band (prediction is [Jhana > Rest])**	**Alpha1 Band (prediction is [Jhana > Rest])**	**Beta Band (prediction is [Jhana > Rest])**	**Gamma Band (prediction is [Jhana > Rest])**
1. Internal verbalization fades	Broca (BA44,45) Wernike (BA39,40)	[.254,.231] F=6.3* [.299,.272] F=8.6*	[.293,.257] F=13** [.424,.414] F=1		
2. External awareness dims	L Visual (O1) L Visual (O2) L Auditory R Auditory (BA41,42)	[.292,.228] F=15** [.299,.225] F=21** [.256,.237] F=4.4* [.272,.225] F=26**	[.405,.362] F=12** [.400,.347] F=16** [.322,.299] F=6.0* [.378,.320] F=29**		
3. Altered sense of personal boundaries	PSPL (P1) PSPL (P2) PSPL (P3) PSPL (P4)	[.259,.210] F=16** [.267,.212] F=24** [.272,.225] F=16** [.303,.236] F=29**	[.333,.296] F=11** [.376,.315] F=19** [.388,.354] F=9* [.438,.385] F=23**		
4. Fewer evaluations, goals, "shoulds"	DLPFC (F3) (F4) (F7) (F8)	[.284,.334] F=25** [.303,.338] F=8* [.273,.289] F=3.5 [.296,.324] F=5.4*	[.248,.213] F=26** [.251,.222] F=15** [.296,.269] F=9.8* [.293,.245] F=27**		
5. Attention is highly focused	ACC (Fz) (FCz) (AFz)			[.359,.338] F=6.9** [.390,.383] F=.8 [.348,.313] F=20**	[.181,.172] F=2 [.183,.202] F=12** [.181,.162] F=11**

*p<.05
**p<.001

Abbreviations: BA=Brodmann Area, PSPL=posterior superior parietal lobule (BA5), DLPFC=Dorsolateral Prefrontal Cortex (BA9,46), ACC=Anterior Cingulate Cortex (BA 32,33).

Fig. 1. Map of power in 6 bands while subject was in Jhana as a ratio of power in the corresponding band when subject was in Resting state. Larger boxes indicate larger deviations from a null hypothesis that Jhana equals Rest state power. Open boxes indicate ratio is smaller than one, so that power in Jhana is less than that in Rest. Filled boxes indicate the ratio is larger than one. Boxes are proportional to log of the ratio of power for the mean of Jhanas 2-8 relative to the mean of Rest states. Power for each electrode for each epoch is measured relative to average power for the entire range of 4-42 Hz..