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Enhanced EEG alpha time-domain phase synchrony during Transcendental Meditation: Implications for cortical integration theory

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Abstract

Information transfer and integration in the brain that leads to high-level cognitive processes requires neuronal coordination. High phase synchronization (zero-lag) in fast frequencies is implicated in integrating sensory events. Alpha EEG activity, long regarded as a passive "idling" frequency, is now being implicated in this integrative function. As an example, in brain pathology decreased alpha phase synchrony is correlated with a decline in cognitive function. Transcendental Meditation (TM) provides an interesting starting point to study neuronal coordination because the "transcending" experience is a baseline state of consciousness, a condition of restful alertness without cognitive activity. Previous work on TM, reported to increase numerous indices of mind–body health, has been shown to increase neural coherence in the alpha band. In this study 15 subjects practicing the TM technique were investigated for changes in alpha phase synchrony. A time-domain method was used to measure millisecond phase shifts in 19 electrodes in long-term practitioners of TM in two conditions: eyes-closed resting and meditation. Significant reductions in millisecond phase lag were found during the meditation condition as compared to the eyes-closed resting condition in 30 of 49 long-range electrode pairings between frontal and occipito-parietal areas. Under the same conditions, twelve control subjects without meditation experience showed no change in alpha phase synchrony over the same time period. It is proposed that enhanced phase synchrony in the alpha frequency during meditation may improve functional integration and may

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have implications for performance and mind–body health. A short proposal for a phase synchrony model of consciousness is included.

Keywords: Phase synchrony; Alpha EEG; Ground state; Meditation; Brain integration; Binding

1. Introduction

Signal processing methods generated by physicists, mathematicians and electrical engineers are accelerating and transforming the field of neuroscience. With the EEG findings arising from "borrowed" signal analysis methods, phase synchronization is emerging as the dominant paradigm used for modeling neuronal coordination in the brain [1]. With such investigative tools important issues such as learning, multi-modal functional integration or "binding", discontinuous perceptual frames and the neural "comparator" necessary for perception are being tied together experimentally to structure a complete theory of consciousness. These aspects have been discussed in a comprehensive theory described as the "neurophysics of consciousness" [2]. Much of the content in the discussion section of the present article follows the structure of this theory. Zero-lag phase synchronization events in the brain are of central importance in the theory.

Some neuroscience theorists who were originally trained in the physical sciences have described the difficulty "for researchers with different backgrounds to communicate subtle ideas or even to form well-posed questions about brain information processing"[3]. Even with this, researchers from different perspectives are gradually integrating disparate methods and discoveries to comprehend the machinery of the mind. Neuroscientists are using concepts borrowed from physics in an attempt to describe neural behavior and "to engage the interest and active participation of physicists and mathematicians in the study of brain dynamics." [4]. In the present article, some ancient understandings and technologies of consciousness associated with meditation practices are added to the diverse mix of conceptual formulations [5].

2. Background

Synchronization in the brain is ubiquitous. The mean zero phase coherence at all frequencies in the brain is between 40% and 65% [6]. The duration, growth rate, frequency and strength of neural coupling are important aspects in the study of performance and brain pathology [1,7]. Neuroimaging methods show 'hotspots' of localized brain activity whereas EEG connectivity measures such as synchrony and coherence reveal more direct evidence of functional *integration* of distant brain activities. Phase synchronization may thus be viewed as a mechanism to accomplish complex cognitive tasks by recruiting spatially distributed neural populations [8].

Historically, the word "synchrony" has been used to describe high-amplitude events reflecting large neural populations firing within the same cortical areas such as in seizures, mid-line anterior theta bursts [9] or in 'hedonic hypersynchrony' in children described in early research [10]. Phase synchrony terminology as referenced here, is independent of amplitude. It is common to see low-amplitude events that have a high value of phase synchrony. Different phase synchrony analysis methods are used to quantify *the degree of precise timing* of oscillations arising from separate or contiguous brain areas [11].

Phase synchrony as used here describes quantitatively the degree to which two signals are "in phase". The earliest published method of measuring phase synchrony was a simple voltage averaging method published in 1965 [12].

Phase synchrony measures have been utilized to discover the occurrence of zero-lag "gamma" frequency events (around 40 cycles/s) between widely separated brain areas [13–15]. The discovery of gamma activity in perfect phase (with "zero-lag") over distributed neural regions presents scientists with a phenomenon that is inconsistent with traditional understanding of traveling waves whose speed is determined by nerve conduction velocities and synaptic transmission time. Zero-lag is of particular research interest because it represents a mechanism to account for brain integration or "binding".

Phase synchrony and phase coherence are related measures. Phase synchrony reflects the degree of leading or lagging relation between EEG signals from electrode pairs; phase coherence reflects stability of phase relationship between electrode pairs, independent of leading and lagging relationships. One advantage of phase synchrony over coherence is that phase synchrony can detect zero-phase lag events thus it may be more meaningful in the investigation of information transfer and integration in the brain.

Several methods have been developed to measure phase synchrony. The method chosen for the present study calculates the millisecond time delay between two signals by counting the number of digitized steps between oscillatory peaks based on a "best fit" sliding comparison. Also included in the category of time-domain analysis is the Hilbert transform [8] that measures the amount of time two signals are in phase. Frequency-domain methods based on the Fourier transform are also used [16]. Other methods include Morlet wavelet analysis [7,17] and various methods of phase-locking to stimulus [18]. The advantages and limitations of phase synchrony methods have been discussed recently [19] and a highly readable summary of the relationship of phase synchrony and coherence has been published [11].

2.1. Alpha phase synchrony in the integration of brain function

Low frequency cortico–cortico interactions serve to integrate multiple simultaneous brain activities [20,77]. Increased synchrony and coherency in the alpha frequencies has been found during cognitive and creative tasks [21–23,76]. During I.Q. and mental rotation tests, greater connectivity is found between frontal and central [24] and frontal and parietal [25] brain areas in induced upper alpha frequency.

Besides synchrony in spontaneous EEG and during tasks, some research recently has looked at 'phase locking' of alpha in relation to a stimulus. The research suggests that a re-setting of phase occurs at the onset of a stimulus. Though phase locking is not a measure of phase synchrony, it does appear to "initialize" alpha to sensory input and may have implications for information transfer in the brain. The 'phase locking index' has been developed to quantify the phase re-setting of alpha in response to a word or picture. Good memory performers show a greater magnitude of phase locking in alpha during recognition in the time window of the evoked potential [26–28].

Enhancement of synchrony has also been seen during attention and vigilance [29]. Cortical synchrony in alpha is enhanced by such influences as learned associations with a stimulus and the actual behavioral context and expectancy [30].

Deficiencies in long-range phase synchrony have been tied to pathology in mania and seizure patients [11]. Low levels of long-range (fronto-parietal) alpha 'synchronization likelihood' have been associated with mild Alzheimer's dementia involving memory loss and disorientation [31]. In a large-scale study, patients with varying degrees of cognitive decline in Alzheimer Dementia were analyzed using Global Field Synchronization (GFS), a measure of global EEG synchronization. GFS reflects the global amount of phase-locked activity at a given frequency. Decline in patients' performance correlated with decreased phase synchrony in alpha, beta and gamma frequencies [32]. Deficiencies in phase synchrony in clinical populations confirms the general hypothesis of a neural "disconnection syndrome" [33].

2.2. Enhancing alpha phase synchrony

Since healthy phase synchrony may be associated with improved cognitive performance and normalized clinical symptoms, it is important to investigate methods that may enhance phase synchrony. These methods include trans-cranial magnetic stimulation and meditation practice.

Repetitive trans-cranial magnetic stimulation (rTMS) induces a strong magnetic field into the brain at close range at different stimulation rates.

Subjects stimulated at the alpha rate with rTMS showed improvements in performance [34] in a mental rotation task. The rTMS procedure has shown promise in improving several disease categories including pain and depression [35] and Parkinson's [36]. Transcranial magnetic stimulation given to patients with various movement and psychiatric disorders was found to increase alpha coherence [37]. The authors suggest that rTMS modulates inter and intra-hemispheric connectivity. The clinical improvement through rTMS is usually transient.

Transcendental Meditation (TM) like rTMS results in elevated levels of alpha EEG coherence, and could also result in increases in phase synchrony. The occurrence of heightened alpha EEG coherence during TM practice was first published almost 30 years ago [38]. Since that report, alpha phase coherence during TM has been reported to (1) increase within two weeks TM practice compared to the eyes-closed baseline session [39]; (2) correlate with improvements in cognitive and emotional parameters such as moral reasoning, emotional stability and anxiety [40]; (3) increase within the first minute of TM practice compared to eyes-closed rest in the same subjects, and remain at that high levels throughout the session [41]; and (4) increase during computer tasks, outside of meditation, with regular TM practice [42]; and (5) associate with positive outcomes in a broad range of patient categories including schizophrenia and depression [43]. Except for a brief mention in an early paper [44] and a recent abstract [45], no TM research has quantified phase synchrony—only EEG coherence has been analyzed.

2.3. A model of brain–mind functioning and meditation

Current theoretical articles have suggested the study of low-cognitive-activity states in order to gain insights in the experimental analysis of consciousness. One article on neocortical dynamics defines a separate role for global (3–16 Hz) and local (above 16 Hz) EEG frequencies [3]. Global frequencies are proposed to unify events over the whole cortex, whereas local frequencies represent isolated sensory activity. States of minimum cognitive activity often exhibit global (widespread), spatially coherent EEG data. The model suggests the testing brain states that are close to the extreme ends of local-global EEG frequency gamut, i.e., a "pure global state" [3, p. 385]. Some meditative states such as "transcending" represent the far extreme of global states involving minimum cognitive processing.

Another theoretical framework specified in meditation theory as well as neuroscience theory is the conceptualization of a "ground state" of consciousness as a basis for understanding active mental states in the brain. The neuro-physics of consciousness theory [2] uses this framework. Some authors have designated the sleep state as the ground state [46]; others have selected eyes-closed resting [2], or waking up in a dark room [47] as the ground state.

To describe how the TM program minimizes cognitive activity and creates a "ground state of consciousness", we place it in a model of brain/mind functioning[1] from the ancient oral and written texts of the Vedas [5]. From this perspective the mind is modeled with a vertical dimension—from active thinking and planning on the surface to more silent field properties at its depth, to a baseline of the mind, a state of pure wakefulness—alertness without activity of thoughts and feelings [40,41]. This state is called "restful alertness" [78,79] and is associated with heightened EEG coherence and periods of spontaneous breath quiescence [41,75].

Much attention has been given to the study of "contents" of consciousness and "process" of consciousness but now through the meditation

[1]The use of full mental potential. "The art of bringing the transcendental Being to the level of the mind simultaneously enlarges the conscious capacity of the mind and enables the full mind to function. It has the advantage of bringing to action all the potentialities of the mind: nothing remains hidden, nothing remains subconscious, everything becomes conscious. This makes every thought a very powerful thought. Again while dealing with the cosmic law we have seen that when the mind comes to that field of the Being, it is naturally set in the rhythm with all the laws of nature and in tune with the process of cosmic evolution." Maharishi Mahesh Yogi, 1966, The Science of Being and the Art of Living, Signet Press, George, Allen and Lunwin, London.

model the study of "consciousness itself" is feasible. This model of consciousness delineates three aspects of experience; knower (consciousness itself), known (contents of consciousness) and process of knowing (process of consciousness, connecting knower and known). The meditation model[1] emphasizing three-in-one nature of consciousness suggests that during meditation the three (the knower, the known and process of knowing) become unified in a state of I-ness, Amness or Being [48]. This meditative state is thus completely self-referral as apposed to object-referral [40]. Activity arising from the meditative ground state is represented as contents and process of consciousness; that is, specific sensory and cognitive processing can be viewed as activation of the ground state.

In a recent journal article a prominent Indian physiologist calls for research into this self-referral state of thoughtless awareness or "turiya avastha".

> It has been common knowledge to oriental thinkers for many centuries, that there are many further states of the human mind, culminating in the state of thoughtless awareness; the fourth state of consciousness. This state must have a physiological basis. The complicated structure of the brain, the extravagant abundance of neural and glial elements in the brain, the infinite possibilities of synaptic junctions and synaptic transmission, and the multitude of neurotransmitters and neuromodulators; all these point to the definite possibility of a much greater level of performance and achievement for the human brain than has been apparent so far. Not only the theories but also the experience of Eastern seers have shown that the brain can transcend the boundaries of logic and reason, and experience states of awareness, commonly unrecognized. In the past few decades, knowledge about the functioning of the human brain has been growing exponentially and scientists of diverse disciplines are concentrating on unraveling its mysteries. It is necessary for scientists to investigate this state with all available tools and find the neurophysiological basis of this state [49].

2.4. EEG theta and meditation research

Enhancement of alpha and theta activity has been historically tied to meditation and attributed to increased brain "idling". Lately, rhythmical frontal midline theta has been tied to specific cognitive states such as during numerical tasks [50] and internalized attention and positive emotional experience during meditation [51]. Though alpha and theta are considered to involve overlapping and similar brain networks [52], there is increasing evidence from evoked potentials and memory studies [28] that they must be dealt with separately. Early in the process of narrowing the topic for the present research it was decided to limit the focus to the alpha frequency for the sake of clarity. Theta topics will be addressed in a separate study.

3. Purpose

The purpose of the present research is to investigate the effects of the TM technique on EEG alpha phase synchrony.

4. Methods

We have chosen here a time-domain method that measures the millisecond time delay between two signals.

4.1. Subjects

Experimental Group: Fifteen individuals (nine males and 6 females) responded to an advertisement in the TM center to participate in a study of the EEG dynamics during TM practice. The subjects had at least 25 years of regular practice of TM twice a day (average 27.2 years). Their age ranged from 46 to 63 years and averaged 54 years. An EEG experiment was performed on an additional long-term meditator who was also analyzed for experiences in TM associated with respiration suspension.

Control Group: 12 volunteers (7 males and 5 females) with no experience with meditation of any type served as Controls. They were friends and colleagues of the TM study participants. These subjects were of the same gender mix, education and age as the TM group (45–61 years, average age 55). Most participants in both groups had advanced college degrees. All subjects were free of psychotropic drugs, and had no history of medical problems or brain injury that might affect the EEG.

4.2. Procedures

This was a within-subjects design. The experiment began with a 3-min eyes-open habituation period. The EEG was then recorded during a 3 min eyes-closed rest condition that was followed by a 20-min TM session and a 15-min rest period for the controls.

TM subjects were instructed:

> Please sit quietly with eyes closed without meditating for a three minute control period.

Then they were instructed to begin their TM practice. At the end of TM the subjects were asked to end the meditation and to keep the eyes closed for an additional 3-min transition period.

Controls were given a 3-min eyes-closed period. Then they were asked to "not practice any mental technique but merely to sit comfortably, keep the eyes closed and think about nothing in particular, just ordinary thinking" for an additional 15 min period.

4.3. Test apparatus and data acquisition

All subjects are tested using Lexicor Neurosearch 19 channel EEG equipment with auxiliary channels. EEG was filtered by anti-aliasing filters (high pass 2 Hz, low pass 64 Hz) with a cut-off frequency of 256 samples per second (gain setting 32 K and a 60 Hz notch filter). In a sound-attenuated room *S*s were seated comfortably for scalp preparation and electrode application using the ECI International electrode cap with elastic band cap with conventional 10–20 placements. Electrode locations included Fp1, Fp2, F3, F4, F7, F8, Fz, C3, C4, Cz, T3, T4, T5, T6, P3, P4, Pz, O1, O2 with a ground between Fz and Cz. Reference was linked ears built into the cap. Electrode impedance is lowered to below 10 kΩ at each electrode site.

In one additional TM subject, a respiration recording was made along with the EEG in order to monitor sub-stages of meditation as seen in the respiratory patterns. The pneumograph manufactured by J & J Equipment was integrated through the auxiliary channels of the EEG unit and respiration was recorded and visually monitored in the lower part of the data screen.

4.4. Data analysis

Data was artifacted by experienced EEG technicians to remove data segments contaminated by muscle or eye-movement activity. Excursions of greater than 100 μV due to artifact were excluded. EEG editor software EEG32 allows editing on the computer screen. Utilizing a standard data selection protocol [32] the first 40 s artifact-free data segments were selected within each subject under eyes-closed resting conditions. Subsequently, the first forty seconds of artifact-free data was edited from periods beginning after 10-min of TM (for the TM group) and after 10 min of EC rest (for the Controls).

Data was originally sampled at 256 data points per second and automatically re-sampled at 100 Hz in the *Neurorep* quantitative EEG analysis software (Grey Matter Inc. of San Rafael, California). In this program data is processed with a two stage (4 pole) Butterworth band pass filter into frequency bands according to the following demarcations: delta .5–3.5 Hz, theta 3.5–7 Hz, alpha 7.0–13 Hz; beta 13–22 Hz. Data epochs are of 1-s duration. The 171 possible pairs are analyzed for millisecond phase lag.

The *Neurorep* software calculates the millisecond time delay in each pair of electrodes in each frequency band. This is accomplished by taking two signals aligned with alignment bars so that the two signals are locked in time the way they were when they were recorded. There are 100 time points end to end in the one second of data. One signal is shifted systematically one digitized step in relation to the other with the signal being shifted in both directions for 31.2 ms. At each time point a correlation coefficient for the paired signal values is calculated. The highest correlation point is thereby determined. The difference of that point and the original position gives the time lag. In each 1-s of data there may be a delay, or the two signals may be exactly at the original position (zero-lag). For an example the highest correlation is one digitized step out of phase then the delay would be 10 MS (1000 ms divided by 100 samples/s). The value "10" would be one of 40 values averaged for each subject to get an average ms delay. That number which is the mean of 40 s of data was used in the statistics.

4.5. Statistical analysis

The *Neurorep* analysis of the 40 s of data yields 171 raw scores representing the average millisecond delay in each of 171 electrode pairs. Four sets of data were generated: (1) TM subjects with eyes closed and (2) TM subjects after 10 min of meditation; also (3) Control group during EC and (4) Control group after 10 min of an additional EC recording period. The Control experiment was a test to see if the passing of time under these conditions would create phase-lag changes.

In the first stage of statistical analysis we performed multiple *t*-tests on the difference in phase synchrony between the two periods- eyes-closed and TM practice in the experimental subjects and eyes-closed and eyes-closed in the control subjects. This resulted in 342 *t*-tests—171 electrode pairs within each group of subjects. Also, a correlation analysis was performed to examine trends in the anterior–posterior (A–P) phase lag changes as compared to left–right (L–R) activity during TM. The raw tracings of the records were visually inspected to observe non-statistical trends in the behavior of phase patterns. Additionally, the mean value of phase synchrony from the sum of the 171 electrode combinations was compared within-conditions.

5. Results

The analysis method yielded an orderly and consistent depiction of phase activity.

Traveling waves showed proportional phase lag increases across the scalp. Millisecond phase lags typically increased from a few milliseconds at Fp1-F3 then ~14 ms at Fp1-C3; ~29 ms at Fp1-P3; and ~48 ms at Fp1-O1. The results showed three distinct global patterns of phase topography: traveling waves (type A), anti-phase zero-lag pattern where front and back brain areas were out of phase (type B) and a zero-lag condition over the whole cortex (Type C). Statistical results show increased long-range A–P phase synchrony during TM and this is attributed to increases in the global zero-lag pattern. The low time lags of Type C averaged with the intermediate and high phase lag values of types A and B yielded lower lag values during TM as compared to eyes closed.

Previous TM studies have primarily found changes in alpha coherence in frontal regions, especially F3–F4 derivations. This study presents a new category of findings, namely strong increases in A–P connectivity.

A number of significant A–P changes in phase lags were noted in the TM group. Table 1 shows the electrode pairings and levels of significance for EC vs. TM. There were 31 electrode pairs that showed significant decreases in phase lag from eyes-closed to TM practice. The significance threshold was set at 0.05 however some pairings reached 0.004. There were no significant differences in phase lag in the control group. Just sitting for 15–20 min did not result in phase lag changes.

Thirty of the TM related-changes were long-range A–P connections. One of these (Fz-F3) was a short-range (adjacent) connection. Also, two posterior connections (T6-O2 and P4-T5) showed increases in phase lag during TM. Fig. 1 shows the brain areas with significant phase lag changes: Fig. 1A shows phase lag reductions and Fig. 1B shows phase lag increases.

The analysis of A–P, L–R difference in phase synchrony showed that the level of significance increased with distance in A–P connections, but not in the contralateral (L–R) connections ($P<0.01$). The correlation coefficients are presented in Table 2. The difference (of phase difference between channels) comparing EC vs. TM correlated significantly positive with the A–P distance between the electrodes of the 171 pairs of

Table 1
Means, standard deviations and significance levels of differences in alpha phase synchrony in 30 long-distance electrode pairings (values are averages of 15 subjects)

	Mean EC	Mean TM	S.D. EC	S.D. TM	Mean Diff.	S.D. Diff.	*P*-Value df = 14
T5-F1	24.17	18.50	18.79	13.82	−5.67	10.16	0.05
T5-F7	18.70	15.50	17.03	13.70	−3.20	4.86	0.02
T6-F4	22.00	17.17	17.82	13.78	−4.83	10.71	0.009
O2-F3	21.75	14.72	17.48	15.05	−7.03	7.9	0.004
O2-F4	24.06	14.63	16.50	14.09	−9.43	12.3	0.01
Fz-T5	21.03	16.29	17.90	13.60	−4.74	6.65	0.02
Fz-P3	14.20	6.34	15.30	6.20	−7.86	11.56	0.02
Fz-P4	16.90	8.76	17.50	11.55	−8.14	11.78	0.02
Fz-O1	24.70	17.70	19.18	14.90	−7.00	11.64	0.04
Fz-O2	24.40	15.90	19.40	15.60	−8.50	3.86	0.02
Pz-F1	14.57	6.08	16.52	8.58	−8.49	13.16	0.03
Pz-F2	16.08	7.12	16.77	8.60	−8.96	12.88	0.02
Pz-F7	10.96	6.40	12.97	8.60	−4.56	6.34	0.02
Pz-F8	15.09	7.20	15.34	8.36	−7.89	11.3	0.02
Pz-F3	8.03	4.50	11.61	6.43	−3.53	5.69	0.03
Pz-F4	9.82	5.66	11.65	6.40	−4.16	6.05	0.02
P3-F1	17.89	9.10	17.56	9.47	−8.79	12.99	0.02
P3-F2	20.01	10.38	17.83	9.30	−9.72	8.53	0.01
P3-F7	12.62	7.83	13.24	8.62	−4.79	5.43	0.004
P3-F8	20.09	9.00	17.22	8.64	−11.09	14.9	0.01
P3-F3	9.72	5.43	11.64	5.84	−4.29	5.80	0.02
P3-F4	13.65	6.72	13.81	6.47	−6.93	10.57	0.02
P4-F1	19.20	10.70	18.35	13.90	−8.50	13.34	0.03
P4-F2	20.25	11.60	18.82	13.77	−8.65	13.65	0.03
P4-F7	18.36	12.85	17.49	15.82	−5.51	8.45	0.02
P4-F8	16.85	8.05	16.27	8.73	−8.80	14.45	0.03
P4-F3	12.10	8.50	15.72	13.28	−3.60	5.24	0.02
P4-F4	13.80	5.97	15.17	7.28	−7.89	12.98	0.02
O1-F3	19.90	16.50	17.50	14.21	−3.40	4.65	0.01
O1-F4	25.13	17.66	18.56	14.10	−7.47	10.62	0.02
Additional pairs of $P<0.05$ significance							
Decrease							
Fz-F3	0.85	0.58	0.49	0.38	−0.27	0.48	0.05 short-range connection phase lag
Increase							
O2-T6	1.22	1.79	0.70	0.93	0.57	0.93	0.03 short-range connection phase lag
Increase							
P4-T5	2.46	3.53	2.16	2.69	1.07	1.91	0.05 long-range L–R connection phase-lag

Left column: Areas of the brain showing significant changes in EEG alpha phase synchrony during TM as compared to rest ($P<0.05$). *Note*: three short-range exceptions at bottom of table.

channels (i.e., the larger the distance between the paired channels/electrodes, the larger was the change in phase synchrony.) but, none of these 4 parameters correlated with the R–L distance between the electrodes of the 171 pairs of channels.

An additional test was a sub-group analysis of averaged difference in phase synchrony across *all sensor pairs* during the eyes-closed and TM period. This was an overall phase synchrony measure that was determined by finding the mean of the 171 phase lag values in each TM subject under both conditions EC and TM. We compared the averages between the two conditions by a within-subjects paired *t*-test. This calculation yielded a significant difference between the two conditions ($t(14) = 3.03$, $P < 0.008$; mean of EC = 7.91 (S.D. = 5.43) and a mean of TM = 6.44 (S.D. = 4.20). This is a global measure of phase synchrony changes during TM and suggests there is an overall reduction in millisecond phase lag, indicating an enhancement of phase synchrony in the brain as a whole.

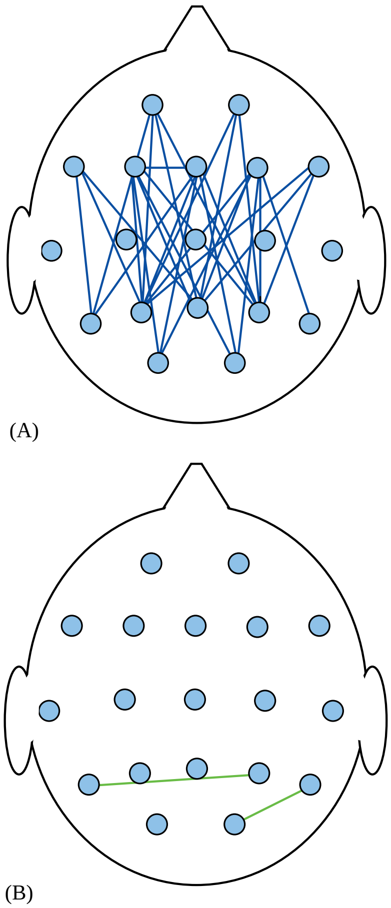

Fig. 1. (A) Long-range anterior-posterior connections showing higher EEG phase synchrony in TM compared to rest. $p < 0.05$. (B) Posterior areas showing decreases in alpha phase synchrony in TM. $p < 0.05$.

Long-range connections TM Group: Long-range connections showed shorter phase lag in 30 of 49 A–P connections during TM as compared to rest at the $P < 0.05$ level or better. The areas affected were T5-F1, T5-F7, T6-F4, O2-F3, O2-F4, Fz-F3, Fz-T5, Fz-P3, Fz-T5, Fz-P3, Fz-P4, Fz-O1, Fz-O2, Pz-F1, Pz-F7, Pz-F8, Pz-F3, Pz-F4, P3-F1, P3-F2, P3-F7, P3-F8, P3-F3, P3-F4, P4-F1, P4-F2, P4-F7, P4-F8, P4-F3, P4-F4, O1-F3, O1-F4. The highest significance values (better than $P < 0.004$) were P3-F7 and O2-F3. One short-range connection in the frontal cortex (Fz-F3) showed significant decreases in phase lag. The connection between right parietal (P4) and left temporal (T5) was the only intrahemispheric L–R pairing that showed significant increase. Also, one adjacent pairing (O2-T6) showed phase lag increase from EC to TM.

To get a better idea of what EEG activity was occurring on a moment-to-moment basis we visually examined the edited segments of the records. We found evidence of phase shifts that appear in the raw unfiltered tracings indicating near zero-lag over the whole cortex. There were three classes of these occurrences: the largest group (9 subjects) showed posterior alpha developing into phase alignments that appeared uniformly among all electrodes. This gives the appearance of neat columns of peaks and valleys that are aligned vertically (see Fig. 2A).

A smaller group of three subjects showed an increased incidence of frontally dominant alpha

Table 2
Correlation analysis of electrode distances and phase lag in milliseconds indicates that anterior–posterior connections were affected more that left–right connections

	Sig. level	Mean EC	Mean TM	Phase diff. EC vs. TM
Correlation coefficients				
Location difference A–P	0.35	−0.84	−0.74	0.73
Location difference L–R	−0.03	−0.05	−0.07	0.00

$P < 0.02$.

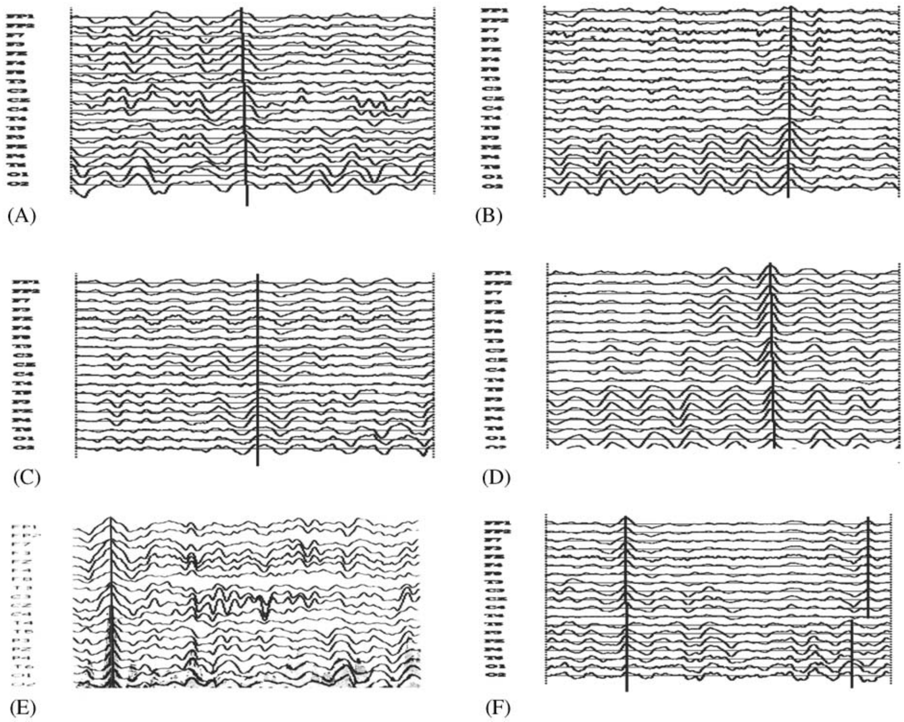

Fig. 2. Incidence of whole-head zero lag alpha during TM. Vertical lines added to highlight phase events. Maximum amplitudes ~60 microvolts. (A) Alpha developing simultaneously over all leads. Examples are from four different TM subjects. (B) Frontally dominant alpha spreading to anterior regions. (C) Anti-phase and in-phase alpha patterns in the same subject.

spreading to the back (see Fig. 2B). In a third group of three subjects alpha appeared out-of-phase in front and back and then came into phase abruptly. These subjects showed short periods when all channels were in phase alternating with short periods when the anterior electrodes were 180° out of phase with posterior electrodes (antiphase, see Fig. 2C). This gives a 'butterfly' appearance to the tracings at the midpoint between Cz and Pz. In one subject monitored with a respirometer, this type of phase alignment consistently occurred within the 5 s preceding suspension of respiration, a marker of maximum depth of TM [75].

The raw scores for each 1-s data epoch were not available; only the mean of 40 s of data was evaluated. The 40 s average phase lag score for most of the TM subjects during EC vs. TM showed a range of 10–60% reductions in phase lag in the long-range connections. It is assumed that the phase shifts toward zero-lag located visually in the EEG records accounted for the reductions in phase lag.

6. Summary of findings

Compared to rest periods the practice of TM produced an increase in alpha phase synchrony primarily between anterior and posterior regions. Control subjects tested under the same conditions did not show increases. Because of the control group results, the findings in TM are not likely to be attributed to passage of time from eyes-closed to meditation.

Patterns in the raw EEG were interpreted as showing an increased incidence of zero-lag alpha events in the brain during TM. Linked-ear reference was discounted as a source of zero-lag through a comparison with linked left and right nostril reference that yielded the same patterns. The prominent feature in the records was episodic phase coordination in the form of vertical columns of peaks. The high incidence of visibly increased phase coordination likely contributed to the A–P time lag reductions.

Some evidence of laterality was seen in the left temporal (T5) area extending to frontal leads. This may be accounted for by the fact that TM involves the use of Vedic sounds that may activate phononic-semantic processing areas underlying T5 location [14]. The millisecond time-lag measures in the right hemisphere at T6 were also lower during TM as compared to EC, though the changes did not reach significance.

7. Interpretation of results: implications for enhanced cortical integration

Zero-lag events are important for the understanding of binding and functional integration in the brain. The following discussion will suggest how increases in alpha phase synchrony found here could have implications for functional integration.

7.1. Explanation of zero-lag events

Neuroscientists have used physics and mathematical concepts to lure more technical-minded researchers into finding explanations of how zero-lag can occur. One extraordinary effort to understand zero-lag phase synchronization events uses terms like ‘‘chaotic itinerancy’’, ‘‘self-organized criticality’’, ‘‘anomalous dispersion’’ and ‘‘phase transitions’’ to account for zero-lag neural events in human and animal experiments [4,13,53]. As an example, the author describes how anomalous dispersion is ‘‘… a well-defined concept from physics can provide a scaffold for the experimental exploration of a phenomenon that might otherwise be overlooked or explained away’’. The author then describes how with anomalous dispersion ‘‘The high velocity of spread of phase transitions can synchronize the oscillations in the beta–gamma range, which in turn express their structure in amplitude modulation patterns.’’

This intriguing theory suggests that the brain maintains a state near a critical recognition point (self-organized criticality) and that a low neural input can create a massive state change in the brain across large distances. The author describes abrupt changes in analytic phase over distances up to 20 cm in humans [4]. These brain state changes create phase locking or zero-lag through a process resembling phase transitions in physical systems. Though the evidence for self-organized criticality is compelling, the nature of this state-change phenomenon is still unknown in neurobiological processes.

With good results, some have used simulations based on neuroanatomy to decipher zero-lag [54]. Simulations of triplets rather than pairs of reciprocally connected areas in the cortical hierarchy showed zero-lag emerging naturally from their three-way interactions. This model may help interpret data involving interactions of top-down vs. bottom-up interactions among different cortical layers.

Others have proposed the physics of standing waves as a mechanism for the creation of zero-lag [55]. Standing waves create a stationary environment in the brain favorable for the formation of information fields and non-local binding processes.

7.2. Traveling and standing waves

Owing to the temporal and spatial structure of the alpha patterns found here and concurrently elsewhere [24], the area of physics theory known as traveling and standing waves is chosen as the favored explanation for zero-lag. This aspect has been described by recent EEG publications [3,55].

Traveling waves occur in the alpha frequency during sensory, perceptual and memory processing [22]. Typically, sensory processing is described as bottom-up or feed-forward processing and perception and cognition are described as top-down or feed-back processing. Feed-forward activity travels from the back to the front of the brain and feed-back activity moves from front to back. Traveling waves appear to carry sensory information but they do not qualify conceptually as a binding mechanism. Only zero-lag or phase-synchronized EEG events have been implicated in multimodal binding.

A recent research article on spatial and temporal aspects of spontaneous alpha phase activity has described two EEG patterns in the eyes-closed resting condition [56]. One alpha pattern (pattern A) was a traveling wave, predominantly front to back (and also to a lesser extent back to front). The direction of the traveling waves was attributed mainly to imagery controlled by top-down influences in eyes-closed conditions.

The other pattern found (pattern B) was an anti phase condition where the front and back of the brain were out of phase by Π radians. In this pattern, the anterior region is in zero-lag in alpha and the posterior area is in zero-lag in alpha but the front and back are out of phase 180°. This condition qualifies as a zero-lag condition though it is divided into two regions, anterior and posterior. Anatomical, functional and topographic studies have agreed with this dual-compartment determination of sensory (posterior) and anterior non-sensory-specific regions [57]. Anesthesia studies have placed the seat of consciousness in the anterior regions. Communication (coherence) between anterior and posterior regions breaks down dramatically under anesthesia [2].

When waves are traveling during sensory events they propagate from sensory to non-sensory specific areas. Conversely when waves are traveling front to back, the cognitive areas extend an influence to sensory areas (see Ref. [22]).

The pattern "B" was first described and attributed to a neural "dipole" distribution of electrical charge [58]. This anti-phase condition also occurs in steady-state visual evoked potentials (SSVEP) [55] and is described as a "standing wave". This SSVEP condition also showed a front/back difference of Π radians with a node at the midline. Our millisecond delay phase analysis technique used in the present study confirmed the finding of pattern B and is attributed to standing wave dynamics.

In several subjects in the eyes-closed condition the front compartment was at zero-lag up to the midline and the back compartment was also in zero-lag. The two areas were approximately 50 ms out of phase. This suggests that every half-cycle of alpha (approximately 50 ms for a 10 Hz wave) the polarity changes creating an anti-phase condition. Combining the results of the time lag and radian methods of phase analysis yields a conclusion that the traveling speed of an alpha wave allows a half cycle of alpha (Π radians) to be in place over the whole cortex every 50 ms. Yet there was a phase shift at the midline. The explanation most likely attributed to the dynamics of a fixed-end standing wave [56]. In a fixed-end standing wave the alternating phase behaves like a reverberating wave. This would mean that a wave traveling from the back of the brain would reverse its traveling direction when it reached the front. The reverberating interference in the bi-directional waves would create standing wave patterns like fixed-end strings on a guitar (Fig. 3).

One author has suggested that the boundary conditions of the cranium, the speed of the traveling waves and the dynamics of firing sequences involved in perception set up a robust mechanism for zero phase lag [3]. Apparently, because of interference of propagating waves on the cortical surface, only certain discrete wavelengths of standing waves can persist as in analog physical systems such as musical instruments. Because of the speed of propagation, the wavelength of alpha and the size of the cranium, the alpha frequency favors the development of standing waves in humans.

7.3. Zero-lag anti-phase alpha may represent the two limbs of a comparator

The segregation of function of anterior and posterior brain areas suggests a role in the comparator process in the brain. A vast body of evidence recently reviewed [2, p. 11] shows that in order for perception to occur there must be an interface between new sensory information and the context of previous experiences. Within 1–500 ms from the point of stimulus, information must be taken in and evaluated for cognitive meaning. The standing wave between the front and back of the brain can provide such a mechanism for inducing long distance synchrony that relates "content" (posterior sensory information) to "context" (anterior representations of past experience).

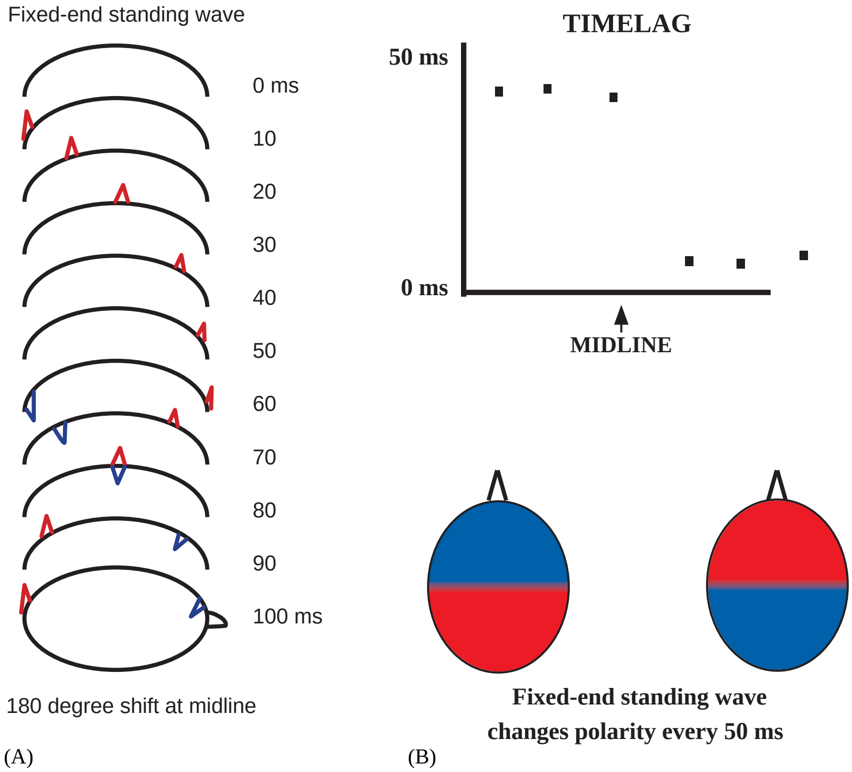

Fig. 3. Graphic representation of time sequence in the development of a fixed-end standing wave in 10 Hz alpha. Wave begins from the back of the brain and after ~50 ms it reaches the front of the brain and begins traveling in the opposite direction and interacts with the negative component of the first oscillation (A). Constructive/destructive interference creates a standing wave pattern with two anti-nodes and one node in the middle (B and C).

Bi-directional alpha can create a standing wave setting up two fields, a subject field and an object field—the two limbs of a comparator. Evidence suggests that nothing happens experientially until the comparison finds meaning in the new stimulus [2, p. 8]. The neurophysics of consciousness theory suggests that "sensation" becomes "perception" when sufficient overlap of the two fields of information occurs. This identification of new sensory input with related past experience creates a loss of ambiguity and a collapse of the two ionic wave functions. These processes are likely reflected in the late components of the evoked potential [59].

It is interesting to note that different cortical layers show phase reversal at different depths in animal implant studies [60]. Thus the different layers of the cortex provide a reasonable framework for interaction of phase in comparator processing. An understanding of the information-carrying properties of antiphase conditions in the brain may also be gained from studying the properties of antiphase lasers [61].

Although quantum models have been suggested for the field "collapse" of the two information fields [2, p. 4] evidence of how this hypothetical comparator occurs has not been presented. It is proposed here that the two anti-phase fields changing polarity every 50 ms constitutes the mechanism of the comparator.

7.4. Zero-lag alpha standing waves may promote gamma binding through "phase-coupling"

Zero-lag gamma oscillations have been implicated in the binding of information in the cortex.

How does this relate to the proposed alpha anti-phase comparator activity? Recent studies have shown *phase coupling* between slow frequencies (alpha, theta and delta) and fast frequencies (beta, gamma) during information processing [30,62,63]. The zero-lag in the slow frequencies (setup by standing waves) combined with phase coupling suggests a mechanism for phase synchrony of gamma. Through phase coupling, low frequencies including alpha EEG rythyms would bind gamma frequency oscillations over long distances thus forming a unified mental construction.

Information fields may be set up for ‘‘content’’ and ‘‘context’’ that are compared every 50 ms until recognition of meaning is established. These time elements are a good fit for early components of sensory-evoked potential studies. Anterior–parietal bursts of gamma occur during face recognition on the point of 200 ms [15]. Based on train duration studies [64] it is suggested that perception may occur at 300–500 ms post stimulus.

This is depicted in the scenario where sub-threshold gamma oscillations are pushed into firing by slow-wave activity [60]. Gamma oscillations may be enhanced by slow oscillations [30,65]. This is supported by the finding that gamma activity occurs at alpha and theta rates in humans [53].

The findings in the present study suggest that during eyes-closed periods traveling waves and fixed-end standing waves occur as information is perceived and evaluated. This time frame corresponds to power peaks of EEG microstates lasting 100–200 ms that correspond to perceptual frames or ‘‘atoms of thought’’ [66] and to link-rate analysis [1].

7.5. Zero-lag in alpha over the whole cortex

Besides the traveling waves and the anti-phase pattern, the present study also found a third type of temporal structure in the alpha frequency (Type C) associated with TM. This was not described in the recent work by others [56]. The dominant pattern in some long-term TM practitioners was a zero-lag condition over the whole cortex *without* a nodal line of phase reversal in the middle. This means that ~ every 50 ms the whole cortex reverses polarity (Fig. 4).

These global zero-lag events accounted for the results of the study that showed an increase A–P phase synchrony (a decrease in phase time lag) during TM. A condition of zero-lag over the whole cortex suggests an open-end standing wave that results from two perfectly timed waves of the same frequency traveling in opposite directions. This kind of wave is not structured through reverberation.

7.6. Alpha global zero-lag condition parallels meditation experience

Standing wave type C may be created when *content* of consciousness is absent. In the contentless state of the deepest point of TM there is no object of attention. The three elements of knower, known and process of knowing (described in Section 2.3) dissolve into a three-in-one structure of ‘‘knowingness’’. The whole cortex in zero-lag alpha represents the total unification and integration of consciousness. Phenomenological studies of TM [48] that agree with ancient descriptions of meditative states. These descriptions include evenness, wholeness, unification, peacefulness.

It is proposed that through the procedure of TM, the signal-to-noise ratio of alpha and gamma oscillations is altered so that gamma firing is decreased along with ‘‘content’’ of consciousness. The alpha is allowed to flow unrestrictedly in both directions without eliciting sensory processing. This agrees with the high alpha/gamma ratios seen in advanced meditators [42]. These distinctions are further supported by the findings of TM cognitive research identifying a shift from ‘‘object referral’’ to ‘‘self referral’’ in advanced practitioners [40].

8. A proposed phase-synchrony model of cortical integration

The findings of the present study suggest a phase synchrony model that has explanatory value in several important components of consciousness theory: multimodal binding, perception, cognition,

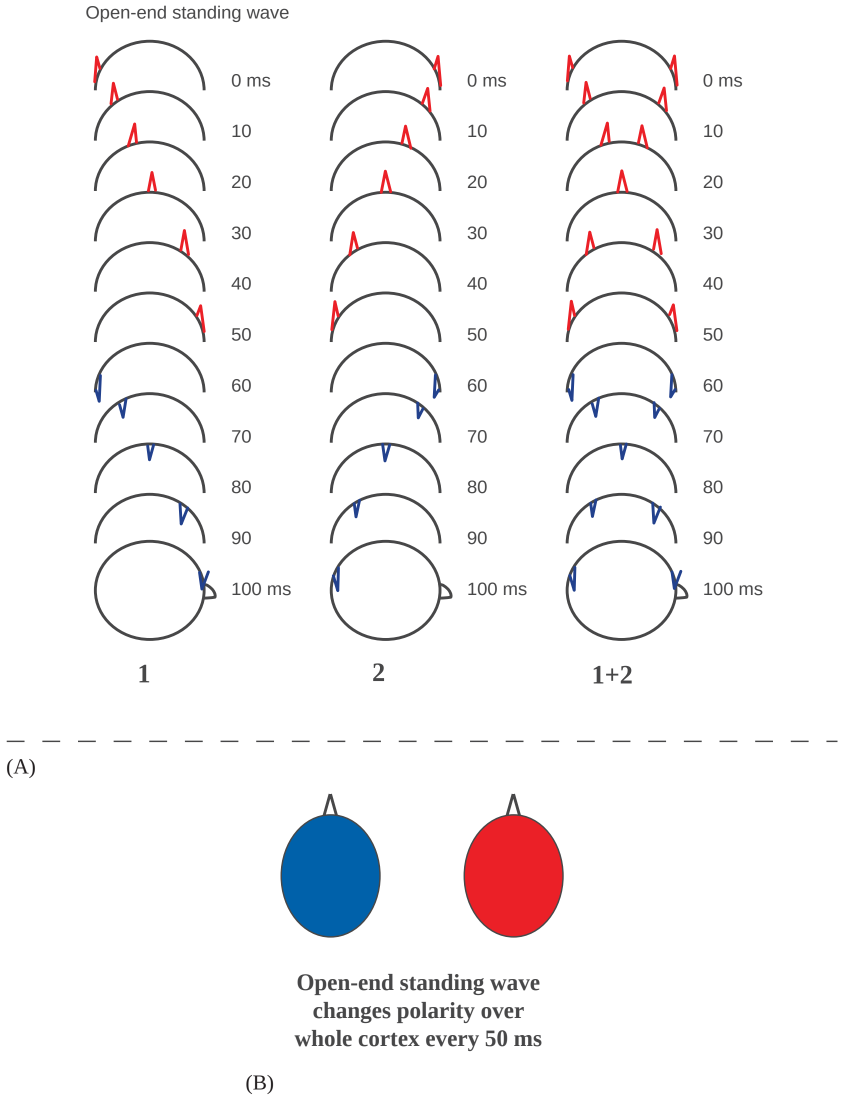

Fig. 4. Model of how open-end standing wave might occur over the human cortex. Two alpha waves of the same frequency (1 and 2) travel in opposite directions to intersect and create a standing wave stationary over the whole cortex (3).

comparator and discontinuity of consciousness that are described as follows:

A signal is received in posterior sensory cortex, ongoing alpha activity is reset to zero (phase-locking to stimulus) and begins traveling across the cortex to anterior regions (P–A direction). This takes about 50 ms and this is the time it takes for the full positive phase of the alpha wave to occur. (A complete cycle of 10 HZ alpha occurs every 100 ms). As the information is received in frontal regions and recognized or compared to previous impressions, a reaction or responsive wave begins traveling in the opposite (A–P) direction. At this instant the P–A wave begins it's negative cycle still traveling in the P–A direction. The two waves intersect and through destructive/constructive interference create an anti-phase standing wave condition with a nodal boundary across the midline. At this point, the anterior regions and posterior regions are undergoing phase reversals with opposite polarity every 50 ms. The front of the brain is in zero-lag and the back of the brain is in zero-lag with the anterior and posterior compartments 180° out of phase.

The positive phase component of the alpha wave enhances sub-threshold gamma modulations and creates a burst of gamma activity alternately in the anterior and posterior compartments at the alpha rate. The process of comparison occurs. In the environment of zero phase lag in both regions the information field of the sensory-specific region is compared to the information field of the non-sensory-specific anterior brain region and if the object is recognized then the two fields interact and a moment of cognitive experience occurs. Sensation becomes perception. This is a non-local cooperative integration occurring across spatially distributed local processes [2, p. 2]. The zero-lag environment resembles a holographic information field. This process represents a mechanism of binding and accounts for zero-lag events in the gamma frequency.

It is during this time of reverberation, interaction and comparison that the early components of the sensory evoked potentials occur. If the stimulus is perceived as significant then late non-sensory components of the evoked potential arise. At about 230 ms a burst of gamma occurs between frontal and parietal regions during face recognition. This corresponds to the late component of the evoked potential. In a related finding during insight, ''aha'' or Eureka experiences a burst of gamma occurs over the right temporal cortex following an alpha burst in parietal association cortex [67].

The time frame of 1–200 ms corresponds to the duration of a microstate [66] described as an ''atom of thought''. Microstate subtype structure supports this model with sensory (posterior) and frontal global power peaks alternating and then also a uniform waveform occurs front-to-back. Microstate episodes have been described as perceptual frames and may correspond to the timing of phase synchronized gamma bursts occurring at alpha and theta rates that are called ''cinematic frames'' [53]. Gamma activity appearing at alpha and theta rates confirms the current hypothesis of phase coupling of alpha and gamma. The phase coupling of zero-lag alpha and fast frequencies may thus perform like an orchestra where the alpha is the conductor and the gamma binding represents the collective functioning of the parts—the different instruments of the orchestra. This may correspond a global resonant state [68] occurring during the ''unity of visual experience''.

9. Implications for mind-body health and performance

In Section 2.1, we reviewed experiments showing that the integrity of phase synchrony is important for mental health and performance. In particular A–P alpha connections are important for cognitive integration. In Section 7.5, we have described a phase model of consciousness showing how zero-lag A–P alpha standing waves might generate functional coupling and binding of gamma frequencies.

In light of the findings of increased A–P synchrony with TM, the performance/clinical significance of TM is highlighted.

TM specifically enlivens long-range neural mechanisms necessary for ''tight functional binding'' [from Ref. 22].

The A–P areas and EEG frequencies enlivened in TM are the same areas that break down in mild Alzheimer's [31]. The one EEG feature distinguishing the patients with mild Alzheimer's dementia with respect to patients with vascular dementia groups, like stroke victims, was a prominent reduction of fronto-parietal alpha. Some of the symptoms of mild Alzheimer's could be attributed to disconnection of the fronto-parietal regions. The symptoms include impairment of language and math abilities along with loss of abstract thinking and planning abilities.

Regarding the improvement of cognitive abilities a recent finding shows that magnetic stimulation (rTMS) in the individual alpha frequency over frontal and right parietal areas enhances performance in a mental rotation task [34]. Even when alpha synchrony is artificially enhanced, there is evidence that phase-coordinated oscillatory activity in the alpha band in A–P areas contribute to the improvement of cognitive performance. New research indirectly supports the model of standing wave in alpha persisting during a visual working memory task. Alpha power and frequency are equalized between prefrontal and occipital electrode sites suggesting stronger functional coupling during manipulation of visual information (top-down processing) [22]. The enhancement of cognitive abilities through TM mentioned in Section 2.2 may be attributable to enhanced A–P connectivity.

Of further significance are the short-range changes in the present study. High values of short-range alpha phase synchrony in frontal regions and lower values of posterior phase synchrony have been discovered to be discriminate functions related to IQ [69]. We found one anterior short-range pair (F3-Fz) that improved phase synchrony and one posterior short-range pair (O2-T6) that showed phase synchrony decrease (longer phase lags) during TM.

The neurophysics model of consciousness [2] as it applies to psychiatric rehabilitation hypothesizes that processes during rest (sleep) restore the nervous system from a perturbed state to a homeostatic ground state [6]. A similar self-regulating model is proposed here with the addition of TM, a wakeful state of quiescence, a ground state, re-integrates mind/body health through a natural phase re-setting process.

It is suggested by the results here that the property of zero-lag in alpha may restore disrupted neural integration mechanisms. Through interference pattern standing waves, alpha phase synchrony may be able to uniquely and holistically enliven cortical fields in the brain.

10. Conclusion: perspectives on phase synchrony

A recent book by a noted physicist on the phenomenon of synchrony [70] describes how from a phycisist's point of view "sync" is mathematically based and has passed the test of experiment. The author describes how sync has offered unified explanations for a wide range of globally cooperative behaviors in living and non-living systems at every distance scale from smaller than the smallest to bigger than the biggest.

Even though the findings here are interpreted with a building blocks perspective, the phase synchrony brain model leaves the door open for deeper interpretations including field interactions, holographic concepts, even quantum field theoretical proposals.

The beauty of phase synchrony is that it can navigate across scales and is compatible with field theory described in a recent field theory of consciousness [18] that is linked to quantum theoretical proposals [71,72]. Phase interactions can occur at different time and distance scales; in fact on the largest scale, the structure of the universe is described as phase coupling of gravitational and microwave fields [73].

Even though the present article develops the thought of standing waves and microstates as the building blocks of experience, the surface phase synchrony may have roots in deeper levels of nature's functioning. A recent book entitled the "Quantum Brain" describes that in biological systems surface levels of order are "nested in and iterated from" deeper levels of nature's functioning [74, p. 209]. In this vein a recent study of phase synchrony behavior using the complex Morlet wavelet analysis method, characterized the alpha EEG as "scale invariant"[7]. The study showed that the growth rate of the alpha fluctuations revealed a hidden order in the dynamics of large-scale synchronized activity suggesting a deeper interpretation of macroscopic data. The building-block theory of consciousness may ultimately give rise to a unified field theory as has been recently suggested [47]. The author of the "Sync" book suggests that the reason that synchrony strikes a chord in all of us is that "we instinctively realize that if we ever find the source of spontaneous order, we will have discovered the secret of the universe".

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And finally we honor the staff of the Signal Processing Journal for recognizing the importance of the area of neuronal coordination and for their promotion and implementation of this issue.

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