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CROSS-SECTIONAL AND LONGITUDINAL STUDY OF EFFECTS OF TRANSCENDENTAL MEDITATION PRACTICE ON INTERHEMISPHERIC FRONTAL ASYMMETRY AND FRONTAL COHERENCE

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Two studies investigated frontal alpha lateral asymmetry and frontal interhemispheric coherence during eyes-closed rest, Transcendental Meditation (TM) practice, and computerized reaction-time tasks. In the first study, frontal coherence and lateralized asymmetry were higher in 13 TM subjects than in 12 controls. In the second study ($N = 14$), a one-year longitudinal study, lateral asymmetry did not change in any condition. In contrast, frontal coherence increased linearly during computer tasks and eyes-closed rest, and as a step-function during TM practice—rising to a high level after 2-months TM practice. Coherence was more sensitive than lateral asymmetry to effects of TM practice on brain functioning.

Key words: coherence, consciousness, frontal lobes, lateral asymmetry, meditation, Transcendental Meditation

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The frontal cortex is considered the top of a hierarchy of neural structures that integrate external information and internal states for the representation, temporal organization, and execution of complex mental and behavioral responses to environmental challenges (Case, 1992; Fuster, 1999). The frontal cortex is reciprocally connected with nearly all other cortices, with subcortical structures, and with many brainstem nuclei (Fuster, 1993, 2000). This extensive neural connectivity supports the role of frontal circuits with attention, learning, planning working memory, language, judgment, moral reasoning, emotions, and self-concept (Ben Shalom, 2000; Davidson & Irwin, 1999; Grady, 1999; Kelley et al., 2002; Vogeley et al., 1999).

Two electrophysiological measures have been used to characterize frontal lobe functioning. One is a measure of interhemispheric power differences, called “lateral asymmetry”; the other a measure of functioning connectivity, called “coherence.” These measures have been used to quantify immediate and long-term effects of meditation practices on brain functioning.

Frontal alpha lateral asymmetry patterns distinguish cognitive task performance and affective states. During predominately verbal tasks, decreased alpha power is reported in the left hemisphere suggesting increased left-hemisphere activation in verbal tasks (Davidson et al., 1990; Tomarken et al., 1990). A disposition toward positive and negative affect has also been characterized by lateral asymmetry patterns (Tomarken et al., 1992). Specifically, positive emotion and, more generally, approach-orienting disposition/behavior toward rewarding stimuli is associated with increased activation in left hemispheric dorsolateral and ventral medial prefrontal cortices, as well as in the left amygdala. In contrast, right prefrontal cortex activation has been observed during certain forms of negative emotion and during withdrawal-oriented disposition/behavior away from aversive stimuli (Davidson, 2002; Davidson et al., 2000a, 2003a).

Recent research reports effects of Mindfulness-Based Stress Reduction (MSBR) program on frontal alpha lateral asymmetry (Davidson et al., 2003b). EEG was recorded in subjects randomly assigned to an 8-week Mindfulness-Based Stress Reduction or to no treatment control during rest and during negative and positive mood induction conditions at baseline, 8 weeks, and 4 months. Mindfulness meditation resulted in significant left-lateralized asymmetry only in central leads, which are predominately over motor cortex (Homan et al., 1987), and there was a trend for significant left-lateralized asymmetry in temporal leads. No significant effects of Mindfulness meditation were reported on prefrontal alpha left-lateralized asymmetry (Travis & Arenander, 2004a), the cortical area most consistently associated with emotional state and health (Davidson, 2002; Davidson et al., 2000a). These data suggest possible influences of meditation practice on EEG interhemispheric power balance.

EEG coherence is a second marker of frontal functioning. Coherence quantifies the phase consistency between pairs of signals in specific frequency bands (Nunez et al., 2001; Thatcher, 1992). Coherence is considered a measure of functional brain connectivity necessary for network formation and integration (Nunez et al., 2001). Lower values of EEG coherence are associated with white matter lesions and decreased cerebral blood flow (Leuchter et al., 1997) schizophrenia (Wada et al., 1998), depression (Leuchter et al., 1997), and normal aging (Kayama et al., 1997). Higher levels of coherence are associated with normal maturation (Thatcher et al., 1986), information exchange (Petsche et al., 1997; Pfurtscheller & Andrew, 1999), and functional co-ordination (Gevins et al., 1989) between brain regions.

Research on Transcendental Meditation (TM) practice,[1] which spans three decades, reports that frontal (F3-F4) EEG coherence (1) is higher during TM practice compared to eyes-closed rest (Dillbeck & Bronson, 1981; Dillbeck et al., 1981; Levine, 1976; Orme-Johnson & Haynes, 1981; Travis et al., 2002); (2) rises to high levels in the first minute of TM practice and continues at these high levels throughout the practice (Travis & Wallace, 1999); and (3) is higher during eyes-open tasks in subjects with more years TM practice (Levine, 1976; Travis et al., 2002). Although early research on effects of TM practice investigated narrow EEG bands (theta and alpha) during TM practice, more recent research suggests that broadband coherence better characterizes Transcendental Meditation practice (Travis et al., 2002).

To compare the sensitivity of these two frontal brain measures to meditation practice, a cross-sectional and longitudinal study was conducted of effects of Transcendental Meditation practice on frontal lateral asymmetry and frontal coherence. No single study has compared both of these frontal brain measures in the same meditation population. To facilitate comparisons with the Mindfulness literature, Davidson's protocol for recording and calculating alpha lateral asymmetry during eyes-closed rest from frontal leads was followed (Davidson et al., 2003b). To facilitate comparison with the TM literature, the authors recorded and calculated broadband frontal EEG coherence during tasks (Travis et al., 2002). The studies reported here focused on these specific measures that

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have been reported in the literature. Future research can expand the measures taken and test brain patterns in different meditating populations.

This study addressed three research questions: (1) How do eyes-closed frontal alpha resting asymmetry and frontal broadband EEG coherence differ in non-TM and long-term TM subjects? (2) What is the strength and direction of correlations of these two brain measures with five measures of psychological and personality traits? and (3) What are the developmental trajectories over one year of TM practice in frontal alpha lateral asymmetry, and frontal EEG coherence during eyes-open tasks, eyes-closed rest and practice of the Transcendental Meditation technique?

EXPERIMENT 1: CROSS-SECTIONAL STUDY OF FRONTAL COHERENCE, FRONTAL ALPHA POWER RESTING ASYMMETRY, AND MEASURES OF PERSONALITY AND PSYCHOLOGICAL TRAITS

Method

Subjects. Twenty-five subjects participated in this study. The first group (Non-TM group) included 13 subjects (5 male and 8 females, age = 37.0 ± 10.5 years),[2] who did not yet practice the TM technique. The other group (long-term TM group) included 12 subjects (6 male and 6 females, age = 42.3 ± 11.2 years), who had been practicing the TM technique for almost 22 years (21.9 ± 11.2 years). The difference in age was not statistically significant ($F(1,24) = 1.46$, $p = .239$). All subjects were right-handed by self-report, and reported good health with no history of accidents, hospitalization, or psychiatric diseases or conditions requiring medication. The non-meditating subjects were recruited from individuals who wished to learn the Transcendental Meditation practice but had not yet been instructed. Thus, these two groups shared an interest in practicing the Transcendental Meditation technique. This research has been approved by the University's IRB, and subjects signed written consent before the research.

Procedure. As part of an earlier study (Travis et al., 2002), EEG was recorded during three conditions: a 5-min eyes-closed resting session, 10-min TM session, and a computer-administered choice reaction-time (RT) task. The choice RT task involved pairs of stimuli—a warning and an imperative stimulus requiring a response. Each trial contained a pair of one- or two-digit numbers

[2]Data are reported as mean ± standard deviation.

(150 ms duration, 1 cm in height) in the center of the computer screen 1.5 s apart. Subjects were asked to press a button in their left hand if the first number was larger, or in their right hand if the second number was larger. To assess psychological health, subjects were later mailed four pencil-and-paper instruments measuring emotional stability, inner/outer orientation, moral reasoning, and anxiety. The mailing was followed up by phone calls. Individuals returned their tests by mail in an enclosed stamped envelope.

Meditation Technique. The Transcendental Meditation technique is practiced while sitting comfortably with eyes-closed. It does not involve attention or control of the breath, or attention to the body, mind or senses, as does Mindfulness meditation (Buchheld et al., 2001). The Transcendental Meditation technique involves turning the attention away from outer phenomena and physiological processes toward more silent states of the mind, which serve as the backdrop for mental activity. Transcendental Meditation practice begins with thinking a mantra—a sound without meaning—and this process of transcending is conducted by "the natural tendency of the mind to expand" (for further discussion see [Maharishi, 1969; Roth, 1994; Travis et al., 2002]).

Measures of Personality and Psychological Traits.

Emotional stability: The emotional stability sub-scale from the International Personality Item Pool was used. The International Personality Item Pool is the result of an international effort to develop and continually refine a set of personality inventories, whose items are in the public domain, and whose scales can be used for both scientific and commercial purposes. The International Personality Item Pool items are freely available on the Internet (http://ipip.ori.org/ipip/). This website reports strong correlations (all $>.80$) with proprietary instruments such as the Minnesota Multiphasic Personality Inventory or the California Personality Inventory. Emotional stability represents the tendency for good emotional adjustment, high self-esteem, low anxiety, security, and easiness with others.

Inner/outer orientation: Baruss developed this scale to quantify a subject's worldview along a material (outer)-transcendental (inner) dimension (Baruss & More, 1992). Subjects are given 38 statements like: "My spiritual beliefs determine my approach to life." Subjects respond on a 7-point Likert Scale. This instrument has high item-total correlations (.56–.62) and high Cronbach alpha coefficients (.82–.95) (Baruss & Moore, 1992). Scores on this scale correlate highly with positive inner growth and meaningfulness of life (Baruss & Moore, 1992). This scale yields a single number, which ranges from −114 (materialistic: "conceptualizing consciousness in terms of information processing") to +114 (transcendental: "emphasize subjective features of consciousness and declare its ontological primacy").

Moral reasoning: Gibbs Socio-Moral Reflection Measure—Short Form presents moral statements and asks subjects to describe *why* a moral act may be important to them. For instance: "Keeping promises is important because . . ."; or "Helping one's friend is important because. . . ." Gibbs has written an extensive reference manual to aid in categorizing responses into moral maturity levels (Gibbs et al., 1992).

The Socio-Moral Reflection Measure can be group administered as a pencil-and-paper test, takes 15–20 min to complete, and can be scored in 25 min. In addition, a scorer can gain competency in 25–30 hours of self-study. Gibbs's Socio-Moral Reflection Measure has high test-retest reliability ($r =$ .88), and high Cronbach alpha coefficients ($r = .92$). Scores on the Socio-Moral Reflection Measure are highly correlated with scores on Kohlberg's Moral Judgment Interview ($r = .70$) (Gibbs et al., 1992), which is much more intensive to administer and to score.

Levels of moral reasoning shift from surface considerations to an inner autonomous basis for decision making. This progress is seen developmentally from childhood to adulthood and parallels growth in cognitive development, ego development, and self-concept (Alexander et al., 1990; Gibbs et al., 1992; Wilber, 2000).

Anxiety levels: Spielberger's State/Trait Anxiety assesses transitory feelings of anxiety (state anxiety) and chronic feelings of anxiety (trait anxiety). High trait anxiety levels are considered a general risk for psychological and physiological disease, perhaps due to the impact of distress on immune response (Friedman & Booth-Kewleys, 1987; Watson & Clark, 1984). Anxiety is one dimension of the emotional stability personality subscale.

EEG Recording Details. EEG was recorded during 5-min eyes-closed rest, 10-min TM practice, and computerized reaction-time tasks from F3, Fz, F4, C3, Cz, C4, P3, Pz, and P4 in the 10–20 system using silver/silver-chloride electrodes affixed with EC-2 cream, a forehead ground, impedances at 5 kohms or less, and a linked-ears reference (for a more detailed description of the methods and tasks see Travis et al. (2002). EEG signals were recorded with a

.01–100 Hz band pass filter (3 dB down, 12 dB octave/slope). All signals were digitized on line at 256 points/s, and stored for later analyses using EEGSYS, a standardized research acquisition and analysis package developed in conjunction with researchers at the National Institutes of Health (Hartwell, 1995).

Data Analysis: Standardized Tests of Personality and Psychological Traits. The tests of inner/outer orientation, state/trait anxiety, and emotional stability were scored using standard templates. Gibbs's moral reasoning protocols were sent to two trained scorers. They met the requirements for reliability in scoring, set forth in Gibbs's manual, Appendix B and C (Gibbs et al., 1992). These two raters correlated .92 on their ratings of the Moral Reasoning protocols. These tests yielded five psychological measures—three of positive psychological traits and two measures of negative traits.

Data Analysis: EEG. Lateral asymmetry was calculated from EEG recorded during the eyes-closed rest period. Broadband coherence was calculated from EEG recorded during the choice reaction time task. This was done to compare with the literature on brain changes during different meditation practices. This EEG analysis yielded two brainwave measures—alpha frontal resting asymmetry and broadband frontal task coherence. These brainwave measures were correlated with scores on paper-and-pencil tests.

Frontal EEG alpha resting asymmetry: The resting eyes-closed data were manually inspected for artifacts, which were marked and excluded from the data analysis (less than 5% of epochs). Following Davidson's protocol (Davidson et al., 2003b), the data were fast Fourier transformed in one-second and epochs during the first two minutes of the eyes-closed session. Frontal (F3 and F4) power was calculated in the alpha frequency (8–13 Hz) (Davidson et al., 2000b; Pivik et al., 1993). The frontal alpha asymmetry score was calculated by subtracting log-transformed left hemisphere alpha power (F3) from log-transformed right-hemisphere alpha power (F4). Greater positivity in this measure is considered to reflect greater left hemisphere activation (reduced left hemisphere alpha activity). It could also mean similar left-hemisphere alpha activity between groups along with increased alpha activity in the right hemisphere in one group or condition.

Frontal EEG coherence during tasks: The first 2-s epochs of each trial were manually inspected for artifacts. Any epochs with artifacts were marked and excluded from the data analysis (less than 7% in these data). These two-second epochs included the 100 ms baseline, first stimulus presentation, 1.5-s interstimulus interval, second stimulus presentation, and 400 ms after presentation of the second stimulus. The actual response, with movement artifacts, occurred after this 2-s period. Thus, this period was relatively free of artifacts and contained a consistent series of cognitive processes. Following Travis's protocol (Travis et al., 2002), these data were fast Fourier transformed in 2-s epochs, and frontal (F3-F4) coherence was calculated in a broadband (8–45 Hz).

Results

The group with extensive TM experience exhibited significantly higher values of frontal alpha asymmetry, frontal EEG coherence, and positive psychological traits, and significantly lower values of negative psychological traits. A MANOVA with group as the between factor and the two brainwave measures and five psychological measures as variates yielded a significant main effect for group (Wilk's Lambda F (7, 17) = 4.65; p = .005). Table 1 contains the means, standard deviations, F statistic, and p-values from individual ANOVAs for the seven variables.

Table 1. Group means, standard deviations, F-statistics (1,24) and p-values for the two frontal brain measures (alpha resting asymmetry and broadband task coherence) and the five measures of personality and psychological traits

	Group	Mean	STD	F Stat	p-value
Rest asymmetry	Control	−0.006	0.054	10.214	0.004
	TM	0.084	0.085		
Task coherence	Control	0.218	0.103	14.88	0.001
	TM	0.391	0.121		
Moral reasoning	Control	3.229	0.448	8.675	0.007
	TM	3.666	0.259		
Inner/Outer orientation	Control	60.203	19.313	10.237	0.004
	TM	82.042	14.175		
Emotional stability	Control	3.288	0.862	14.922	0.001
	TM	4.371	0.462		
State anxiety	Control	34.769	13.700	9.533	0.005
	TM	22.417	2.021		
Trait anxiety	Control	38.615	13.745	10.997	0.003
	TM	25.250	2.417		

Control = 12; TM = 13.

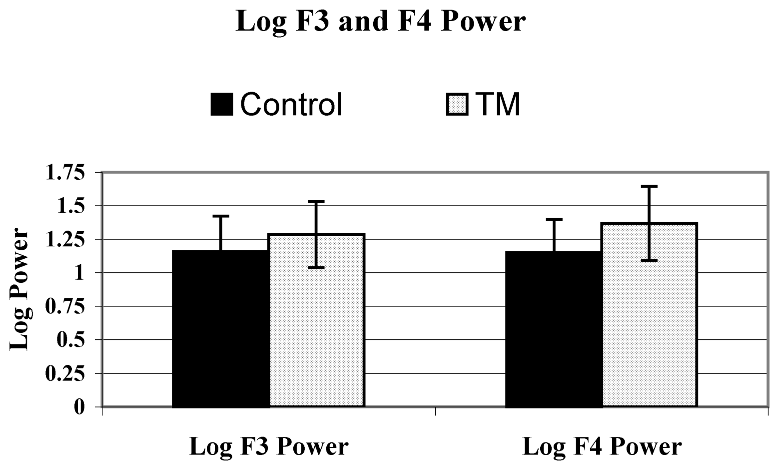

Figure 1. Mean and Standard Deviation of Log F3 and F4 Power in Control and TM Subjects. Alpha asymmetry differences between these groups appeared to have resulted from higher right-hemisphere alpha power.

Because lateral asymmetry is a difference-variable, so-called left lateralized activation could result from greater left-hemisphere activation (reduced F3 alpha power), or greater right-hemisphere (F4) alpha power. Figure 1 presents the log power values at F3 and F4 for both groups. Statistically significant lateral asymmetry values between these groups appeared to have resulted from higher right hemisphere alpha power, $F(1, 23) = 4.28$, $p = .051$. There were no group differences in left hemisphere alpha power, $F(1, 23) = 1.51$, $p = .232$. The TM subjects also had higher alpha power overall (MANOVA, Wilk's Lambda $F(2,22) = 5.86$, $p = .009$). Higher overall alpha power has previously been reported in long-term TM subjects during eyes-closed rest and eyes-open tasks (Travis et al., 2002).

The relations between the brainwave and psychological variables were assessed with a Pearson correlation analysis and are presented in Table 2. Frontal alpha asymmetry correlated moderately with EEG coherence ($r = .33$) and weakly with the five psychological and personality variables (range of $r = .08$ to $.28$). In contrast broadband frontal coherence correlated highly with all variables. Table 2 presents the correlation estimates for these seven variables as well as Spearman *rho* of group with each of these variables. Statistically significant correlations are in bold.

Table 2. Correlation table of five psychological variables and two brainwave variables (Pearson correlation) and group membership (Spearman rho). Statistically significant correlations are in bold

	Asymmetry	Coherence	Moral	Orient.	Stability	State	Trait
Coherence	0.33						
Moral	0.28	**0.55**					
Orientation	0.08	**0.53**	**0.54**				
Stability	0.27	**0.62**	**0.56**	**0.58**			
State anxiety	−0.18	**−0.59**	**−0.59**	**−0.57**	**−0.83**		
Trait anxiety	−0.08	**−0.45**	**−0.55**	**−0.58**	**−0.86**	**0.84**	
Group	**0.48**	**0.62**	**0.52**	**0.56**	**0.68**	**−0.57**	**−0.65**

Discussion

This exploratory cross-sectional study suggests that broadband frontal coherence may be a more reliable measure of TM-related effects on brain functioning. This finding is preliminary because initial group differences are not known in a cross-sectional study. The two groups were similar in many ways—handedness, age, and interest in the Transcendental Meditation technique. There could, however, have been other systematic differences between the two groups that contributed to the observed differences in brain functioning and psychological traits.

The next study used a longitudinal study to more reliably assess the relation of Transcendental Meditation practice, frontal alpha asymmetry, and frontal coherence. This study investigated brain patterns over one year in three conditions: eyes-closed rest, Transcendental Meditation practice, and eyes-open tasks.

EXPERIMENT 2: LONGITUDINAL TEST OF TM EFFECTS ON FRONTAL ALPHA RESTING ASYMMETRY, AND FRONTAL BROADBAND TASK COHERENCE

This second experiment used a longitudinal design with each subject serving as his or her own control. To strengthen the design: (1) subjects were measured at three posttests; (2) non-equivalent dependent variables were measured (task coherence and alpha resting asymmetry), and (3) measurements were recorded during three independent conditions (eyes-closed rest, TM practice, and eyes-open computer tasks) (Shadish et al., 2002, pp. 110–111).

Method

Subjects. Fourteen subjects participated in this study as part of the University's ongoing student evaluation program. Subjects comprised 9 males and 5 females with an average age of 27.5 years ± 9.6 years. All subjects were right-handed, and reported good health with no history of accidents, hospitalization, or psychiatric diseases. This research has been approved by the University's IRB, and subjects signed written consent before the research.

Procedure. EEG was recorded during three conditions: (1) 5-min eyes-closed resting session, (2) computer-administered choice reaction-time task, as described in the first experiment, and (3) 10-min TM practice. All subjects were recorded on this schedule to avoid possible sequence effects of TM practice on subsequent sessions.

EEG Recording Details. EEG was recorded from F3, Fz, F4, C3, Cz, C4, P3, Pz, and P4 using the same filter settings and references as in the first experiment.

EEG Analysis Details. The data were first manually inspected for artifacts. These were marked and excluded from subsequent analyses. Fewer than 5% of epochs contained artifacts in these data. The data were then fast Fourier transformed in one-second epochs during the first two minutes of the eyes-closed rest and TM sessions, and during two-second epochs containing the choice reaction time (RT) tasks, as in the first experiment. Frontal alpha asymmetry, and broadband frontal coherence were calculated as detailed in experiment one during the three conditions—resting, reaction time tasks, and Transcendental Meditation practice.

Statistical Tests. Following published recommendations for psychophysiological measures (Jennings et al., 1987; Keselman, 1998), MANOVAs were used to test for longitudinal differences in coherence and lateral asymmetry. If significance differences were found, then repeated measures ANOVAs were used to investigate the slope of the change over time.

Results and Discussion

Frontal Alpha Power Asymmetry. There were no significant pre–post test differences in alpha asymmetry over the year in any of the three conditions (Wilk's lambda $F(3,11) < 1.0$, ns). There were significant conditions

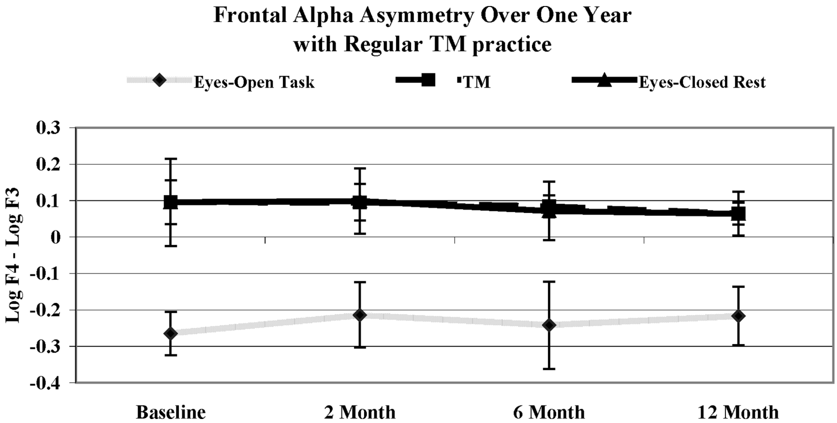

Figure 2. Mean and Standard Deviation of Frontal Alpha Asymmetry Levels over one year in the three conditions. Alpha asymmetry did not significantly change over one year during eyes-closed rest, practice of the Transcendental Meditation technique, or the eyes-open choice reaction time tasks, although there were significant condition differences—the two eyes-closed conditions (rest and TM) had more left-lateralized activation than during the choice reaction time task.

differences, reflecting the demands of each task. Lateral symmetry during eyes-closed rest and Transcendental Meditation practice were significantly more left lateralized that during the reaction time task ($F(2,42) = 10.8$, $p < .0001$) with no differences between the two eyes-closed conditions ($F(1,14) < 1.0$, ns.) Figure 2 presents the frontal alpha asymmetry values at baseline, 2, 6, and 12 months posttest for the three conditions: eyes-open tasks (grey line), eyes closed rest (solid line), and TM practice (dashed line).

Frontal Broadband Coherence. Figure 3 presents broadband frontal coherence values at baseline, 2, 6, and 12 months posttest during eyes-open tasks (gray line), eyes closed rest (solid line), and TM practice (dashed line). Statistical tests revealed significant main effects for both time (pre–post test) and condition (rest, TM, and task) in broadband frontal coherence.

Longitudinal differences: MANOVAs revealed a significant main effect for time in frontal broadband EEG coherence during eyes-open computer tasks ($F(3,11) = 4.9$; $p = .021$), during eyes-closed rest ($F(3,11) = 3.59$; $p = .05$), and during TM practice ($F(3,11) = 5.5$; $p = .017$). Repeated measure ANOVAs revealed a significant linear trend in EEG coherence from baseline to the three posttest-recordings during tasks ($F(1,13) = 14.5$; $p = .002$) and

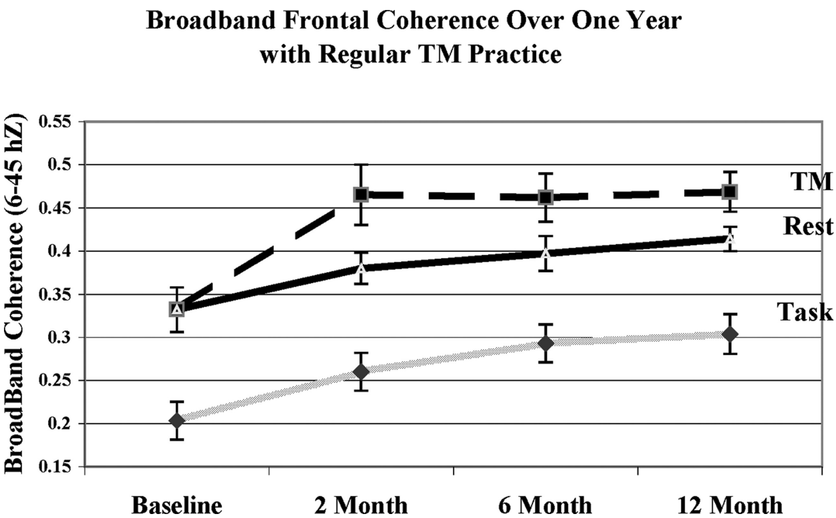

Figure 3. Mean and Standard Deviation of Broadband Frontal Task Coherence over one year. Frontal coherence changed significantly over the one year in each of the three conditions.

during eyes-closed rest ($F(1,13) = 8.8$; $p = .011$), and a significant quadratic trend or step-function in EEG coherence during TM practice ($F(1,12) = 11.8$; $p = .005$). During TM practice, individual comparisons revealed a significant increase in broadband frontal coherence from baseline eyes-closed rest to the 2 month TM recording ($F(1,13) = 18.3$; $p = .001$) and no significant changes in frontal broadband coherence between 2, 6, and 12 month posttests ($F\ (2,24) < 1.0$, ns).

Conditions differences: Within MANOVAs compared broadband frontal coherence between the three conditions. Coherence during TM practice was significantly higher than during eyes-closed rest ($F(1,13) = 8.2$; $p = .013$), and coherence during eyes-closed rest was significantly higher than during the eyes-open computer tasks ($F(1,13) = 29.2$; $p < .0001$.)

Discussion

The findings in this longitudinal experiment revealed that frontal alpha asymmetry did not significantly change during one year of Transcendental Meditation practice in any condition. Frontal alpha asymmetry may be a neurophysiological trait that either does not change due to TM practice or it changes very slowly. This conclusion is supported by other studies that report EEG frontal alpha asymmetry is stable over time across waking, sleeping, and dreaming (Benca et al., 1999). In addition, although Davidson's research reported significant changes in central leads after 8 weeks Mindfulness meditation practice (Davidson et al., 2003b); no significant changes were reported for prefrontal leads (F3 and F4, or F7 and F8) (Travis & Arenander, 2004).

In contrast to the pattern of alpha asymmetry, significant increases in frontal broadband coherence were seen during one-year practice of the Transcendental Meditation technique across all conditions, although the slope within each condition differed. The slope was linear during eyes-open tasks and eyes-closed rest, and quadratic during TM. These coherence findings during eyes-open tasks and TM practice support earlier findings that brainwave changes during TM practice are stabilized after a relatively short period of TM practice, and that the effects of TM practice over time may be more evident in brainwave patterns outside of meditation (Travis et al., 2002).

Possible Effects of a Linked-Ears Reference on the Findings

A linked-ears reference may distort EEG power and coherence spectra. Frontal power spectra of linked-ears reference data often have peaks that correspond to posterior EEG patterns, and the coherence spectra are significantly higher with linked-ears data compared to reference-free data such as close bi-polar or current source density (Fein et al., 1988; Travis, 1994). In this study, possible linked-ears confounds would have been similar in all conditions. Thus, the patterns in coherence and alpha asymmetry over time and between conditions probably reflect conditions-effects rather than reference-artifacts.

GENERAL DISCUSSION

These studies focused their investigation on lateral asymmetry and coherence between frontal leads because these two measures have been reported to best characterize two different meditation practices—Mindfulness and Transcendental Meditation. Future research can extend these findings to include (1) data from a dense-array of frontal electrodes to identify the spatial extent of these findings, (2) contributions of other scalp areas, and (3) effects of using "reference free" data, resulting from a Laplacian transform, on patterns of lateral asymmetry and coherence (Fein et al., 1988; Nunez et al., 2001).

Four conclusions emerge from the current study. First, EEG frontal coherence, compared to alpha frontal asymmetry, appears to be a better index of TM-effects on brain functioning. In the first experiment, larger group differences were seen in frontal coherence than in lateral asymmetry and coherence correlated more highly with measures of personality and psychological traits than did lateral asymmetry. In the second experiment, lateral asymmetry did not significantly change over the year of regular TM practice. In contrast, coherence changed significantly during all three conditions—eyes-closed rest, Transcendental Meditation practice, and choice reaction time tasks.

Nunez explains the possible effects of local, intermediate, and long range or global synchrony on EEG power and coherence (Nunez et al., 2001). EEG power levels reflect the intermediate synchrony between cortical columns (1–3 cm), whereas EEG coherence levels reflect long range or global synchrony between spatial-distributed cortical areas (10–25 cm). Changes in EEG power (intermediate synchrony) thus occur on the "background environment" of global synchrony (Nunez, 2000; Nunez et al., 2001), which facilitates and organizes synchrony between cortical columns. In terms of Nunez's model, practice of the Transcendental Meditation technique appears to enhance the "background environment" of frontal connectivity, as reflected in increased broadband coherence both during the practice and after the practice. Some researchers consider broadband coherence as a mechanism for binding spatial separate cortical activity into the unity of conscious experience (Varela et al., 2001). In this study, increased coherence across a wide band of EEG frequencies may signal a more integrated style of frontal executive functioning that may be termed "whole brain functioning." Previous research reports that increased frontal coherence is associated with improved neurophysiological integration (Wallace et al., 1983), cognitive flexibility (Dillbeck et al., 1981), and performance on attentional tasks (Travis et al., 2002).

A second conclusion is that broadband frontal EEG coherence during tasks appears to be associated with improved cognitive functioning and mental health. Frontal EEG coherence was positively correlated with moral reasoning, emotional stability, inner orientation, and inversely correlated with both state and trait anxiety. Correlations of alpha resting asymmetry with these personality and psychological measures were much lower ($<.30$) and did not reach statistical significance.

A third conclusion is that proficiency in TM practice appears to be achieved after a few months practice. High broadband coherence levels were reached within two months practice of the Transcendental Meditation technique. Coherence estimates remained at these high levels at 6 and 12 months. The lack of apparent TM "practice effects" in EEG patterns may be an important benchmark to help guide future research on TM effects and the efficacy of other meditation practices. This replicates previous findings (Travis et al., 2002).

A fourth related conclusion is that long-term effects of TM practice on brain dynamics are more clearly evident during activity, rather than during meditation. Although significant increases in coherence were seen during TM practice after two months practice, effects of regular TM practice at 6 and 12 months were seen during tasks outside of the practice itself. This replicates previous findings (Travis, 1991; Travis et al., 2002). The unique brainstate cultured during TM practice, as measured by frontal coherence, appears to be integrated with waking brainstates outside of meditation (Travis et al., 2000, 2002) and may provide an enhanced understanding of human mind/body potential (Travis et al., 2004).

Together, the early efficacy of TM practice combined with progressive changes in brain dynamics during waking tasks may constitute two important criteria for understanding the evolution of brain states arising from TM practice. It is possible that these two criteria could serve as benchmarks to compare different meditation techniques, which generate different meditative brain states. In addition, future comparative meditation research may benefit from inclusion of coherence measures across multiple frequency bands, during the practice, as well as during waking tasks. A collaborative effort of different labs could use a common set of brain measures to study their particular meditation tradition. Such a collaborative effort would enhance the understanding of similarities and differences between meditation and spiritual traditions.

REFERENCES

Alexander, C., Davies, J., Dixon, C. A., Dillbeck, M., Druker, S., Oetzel, R. M., Muehlman, J. M., & Orme-Johnson, D. (1990). Growth of higher stages of consciousness: Maharishi Vedic psychology of human development. In C. Alexander & E. Langer (Eds.), *Higher Stages of Human Development*. (pp. 259–341). New York: Oxford University Press.

Baruss, I., & Moore, R. J. (1992). Measurement of beliefs about consciousness and reality. *Psychology Reports*, *71*, 59–64.

Ben Shalom, D. (2000). Developmental depersonalization: The prefrontal cortex and self- functions in autism. *Consciousness and Cognition*, *9*, 457–460.

Benca, R. M., Obermeyer, W. H., Larson, C. L., Yun, B., Dolski, I., Kleist, K. D., Weber, S. M., & Davidson, R. J. (1999). EEG alpha power and alpha power asymmetry in sleep and wakefulness. *Psychophysiology*, *36*, 430–436.

Buchheld, N., Grossman, P., & Walach, H. (2001). Measuring mindfulness in insight meditation (Vipassana) and meditation-based psychotherapy. *Journal for Meditation and Meditation Research*, *1*(1), 10–33.

Case, R. (1992). The role of the frontal lobes in the regulation of cognitive development. *Brain and Cognition*, *20*, 51–73.

Davidson, R. J. (2002). Anxiety and affective style: Role of prefrontal cortex and amygdala. *Biological Psychiatry*, *51*(1), 68–80.

Davidson, R. J., Chapman, J. P., Chapman, L. J., & Henriques, J. B. (1990). Asymmetrical brain electrical activity discriminates between psychometrically-matched verbal and spatial cognitive task. *Psychophysiology*, *27*, 528–543.

Davidson, R. J., & Irwin, W. (1999). The functional neuroanatomy of emotion and affective style. *Trends in Cognitive Neuroscience*, *3*, 11–21.

Davidson, R. J., Jackson, D. C., & Kalin, N. H. (2000a). Emotion, plasticity, context, and regulation: Perspectives from affective neuroscience. *Psychological Bulletin*, *126*(6), 890–909.

Davidson, R. J., Jackson, D. C., & Larson, C. L. (2000b). Human electroencephalography. In J. T. Cacioppo, G. G. Berntson, & L. G. Tassinary (Eds.), *Principles of Psychophysiology*. (pp. 27–52). New York: Cambridge University Press.

Davidson, R. J., Irwin, W., Anderle, M. J., & Kalin, N. H. (2003a). The neural substrates of affective processing in depressed patients treated with venlafaxine. *The American Journal of Psychiatry*, *160*(1), 64–75.

Davidson, R. J., Kabat-Zinn, J., Schumacher, J., Rosenkranz, M., Muller, D., Santorelli, S. F., Urbanowski, F., Harrington, A., Bonus, K., & Sheridan, J. F. (2003b). Alterations in brain and immune function produced by mindfulness meditation. *Psychosomatic Medicine*, *65*(4), 564–570.

Dillbeck, M. C., & Bronson, E. C. (1981). Short-term longitudinal effects of the transcendental meditation technique on EEG power and coherence. *The International Journal of Neuroscience*, *14* (3–4), 147–151.

Dillbeck, M. C., Orme-Johnson, D. W., & Wallace, R. K. (1981). Frontal EEG coherence, H-reflex recovery, concept learning, and the TM-Sidhi program. *The International Journal of Neuroscience*, *15*(3.)

Fein, G., Raz, J., Brown, F. F., & Merrin, E. L. (1988). Common reference coherence data are confounded by power and phase effects. *Electroencephalography and Clinical Neurophysiology*, *69*, 581–584.

Friedman, H. S., & Booth-Kewley, S. (1987). The “disease-prone personality”: A meta-analytic view of the construct. *American Psychologist*, *42*, 539–555.

Fuster, J. M. (1993). Frontal lobes. *Current Opinion in Neurobiology*, *3*(2), 160–165.

Fuster, J. M. (1999). Cognitive functions of the frontal lobes. In B. L. Miller & J. L. Cummings, (Eds.), *The Human Frontal Lobes*. New York: Guilford Press.

Fuster, J. M. (2000). Executive frontal functions. *Experimental Brain Research*, *133*(1), 66–70.

Gevins, A. S., Bessler, S. L., Morgan, N. H., Cutillo, B. A., White, R. M., Greer, D. S., & Illes, J. (1989). Event-related covariances during a bimanual visuomotor task. I. methods and analysis of stimulus- and response-locked data. *Electroencephalography and Clinical Neurophysiology*, *74*, 58–75.

Gibbs, J. C., Basinger, K. S., & Fuller, D. (1992). *Moral Maturity*. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Grady, C. L. (1999). Neuroimaging and activation of the frontal lobes. In B. L. Miller & J. L. Cummings (Eds.), *The Human Frontal Lobes*. New York: Guilford Press.

Hartwell, J. (1995). *EEGSYS User's Guide*. Baltimore, MD: Friends Medical Science Research Center, Inc.

Homan, R., Herman, J., & Purdy, P. (1987). Cerebral location of international 10–20 electrode placement. *Electroencephalography and Clinical Neurophysiology*, *66*, 376–382.

Jennings, J. R., Cohen, M. J., Ruchkin, D. S., & Fridlund, A. J. (1987). Editorial policy on analysis of variance with repeated measures. *Psychophysiology*, *24*, 474–479.

Kayama, K., Hirasawa, H., Okubo, Y., & Karasawa, A. (1997). Quantitative EEG correlates of normal aging in the elderly. *Electroencephalography and Clinical Neurophysiology*, *28*, 160–165.

Kelley, W. M., Macrae, C. N., Wyland, C. L., Caglar, S., & Inati, S. (2002). Finding the self? An event-related fMRI study. *Journal of Cognitive Neuroscience*, *14*(5), 785–794.

Keselman, H. J. (1998). Testing treatment effects in repeated measure design: An update of psychophysiological research. *Psychophysiology*, *35*, 470–478.

Leuchter, A. F., Cook, I. A., Uijtdeharge, S. H., Dunkin, J., Lufkin, R. B., Anderson-Hanley, C., Abrams, M., Rosenberg-Thompson, S., O'Hara, R., Simon, S. L., Osato, S., & Babaie, A. (1997). Brain structure and function and the outcomes of treatment for depression. *Journal of Clinical Psychiatry*, *58*(Suppl 16), 22–31.

Levine, P. (1976). The coherence spectral array (COSPAR) and its application to the study of spatial ordering in the EEG. *Proceedings of the San Diego Bio-Medical Symposium*, *15*, 237–247.

Maharishi, (1969). *Maharishi Mahesh Yogi on the Bhagavad Gita*. New York: Penguin.

Nunez, P. L. (2000). Toward a quantitative description of large scale neocortical dynamic function and EEG. *Behavior and Brain Science*, *23*, 371–398.

Nunez, P. L., Wingeier, B. M., & Silberstein, R. B. (2001). Spatial-temporal Structures of Human Alpha Rhythms: Theory, Microcurrent Scources, Multiscale Measurements, and Global Binding of Local Networks. *Human Brain Mapping*, *13*, 125–164.

Orme-Johnson, D. W., & Haynes, C. T. (1981). EEG phase coherence, pure consciousness, creativity, and TM—Sidhi experiences. *The International Journal of Neuroscience*, *13*(4), 23–29.

Petsche, M., Kaplan, S., von Stein, A., & Filz, O. (1997). The possible meaning of the upper and lower alpha frequency ranges for cognitive and creative tasks. *International Journal of Psychophysiology*, *26*, 77–97.

Pfurtscheller, G., & Andrew, C. (1999). Event-related changes of band power and coherence: Methodology and interpretation. *Journal of Clinical Neurophysiology*, *16*(6), 512–519.

Pivik, T., Broughton, R., Coppola, R., Davidson, R. J., Fox, N. A., & Nuwer, R. (1993). Guidelines for quantitative electroencephalography in research contexts. *Psychophysiology*, *30*, 547–558.

Roth, R. (1994). *TM—Transcendental Meditation: A New Introduction to Maharishi's Easy, Effective and Scientifically Proven Technique for Promoting Better Health, Unfolding Your Creative Potential, and Creating Peace in the World*. New York: Plume Books.

Shadish, W. R., Cook, T. D., & Campbell, D. T. (2002). *Experimental and Quasi-Experimental Design*. New York: Houghton-Mifflin Co..

Thatcher, R. W. (1992). Cyclic cortical reorganization during early childhood. *Brain and Cognition*, *20*(1), 24–50.

Thatcher, R. W., Krause, P. J., & Hrybyk, M. (1986). Cortico-cortical associations and EEG coherence: a two-compartmental model. *Electroencephalography and Clinical Neurophysiology*, *64*(2), 123–143.

Tomarken, A. J., Davidson, R. J., & Henriques, J. B. (1990). Resting frontal brain asymmetry predicts affective responses to films. *Journal of Personality and Social Psychology*, *59*(4), 791–801.

Tomarken, A. J., Davidson, R. J., Wheeler, R. E., & Doss, R. C. (1992). Individual differences in anterior brain asymmetry and fundamental dimensions of emotion. *Journal of Personality and Social Psychology*, *62*(4), 676–687.

Travis, F. (1994). A second linked-reference issue: Possible biasing of power and coherence spectra. *The International Journal of Neuroscience*, *75*(1–2), 111–117.

Travis, F., & Arenander, A. (2004). EEG Asymmetry and Mindfulness Meditation: Reply to Davidson, et al. *Psychosomatic Medicine*, *66*, 147–152.

Travis, F., & Pearson, C. (2000). Pure consciousness: Distinct phenomenological and physiological correlates of "consciousness itself". *The International Journal of Neuroscience*, *100*(1–4), 77–89.

Travis, F., & Wallace, R. K. (1999). Autonomic and EEG patterns during eyes-closed rest and transcendental meditation (TM) practice: The basis for a neural model of TM practice. *Consciousness and Cognition*, *8*(3), 302–318.

Travis, F. T. (1991). Eyes open and TM EEG patterns after one and after eight years of TM practice. *Psychophysiology*, *28*(3a), S58.

Travis, F. T., Arenander, A. T., & DuBois, D. (2004). Psychological and physiological characteristics of a proposed object-referral/self-referral continuum of self-awareness. *Consciousness and Cognition*, *13*, 401–420.

Travis, F. T., Tecce, J., Arenander, A., & Wallace, R. K. (2002). Patterns of EEG coherence, power, and contingent negative variation characterize the integration of transcendental and waking states. *Biological Psychology*, *61*, 293–319.

Varela, F., Lachaux, J.-P., Rodriguez, E., & Martinerie, J. (2001). The Brainweb: Phase synchonization and large-scale integration. *Neuroscience*, *2*, 220–230.

Vogeley, K., Kurthen, M., Falkai, P., & Maier, W. (1999). Essential functions of the human self model are implemented in the prefrontal cortex. *Consciousness and Cognition*, *8*(3), 343–363.

Wada, Y., Nanbu, Y., Kikuchi, M., Koshino, Y., Hashimoto, T., & Yamaguchi, N. (1998). Abnormal functional connectivity in Alzheimer's disease; Intrahemispheric EEG coherence during rest and photic stimulation. *European Archives of Psychiatry and Clinical Neuroscience*, *248*, 203–208.

Wallace, R. K., Mills, P. J., Orme-Johnson, D. W., Dillbeck, M. C., & Jacobe, E. (1983). Modification of the paired H reflex through the Transcendental Meditation and TM-Sidhi program. *Experimental Neurology*, *79*(1), 77–86.

Watson, D., & Clark, L. A. (1984). Negative affectivity: The disposition to experience aversive emotional states. *Psychology Bulletin*, *96*, 465–490.

Wilber, K. (2000). *Integral Psychology: Consciousness, Spirit, Psychology, Therapy*. San Francisco: Shambhala.