

Meditation States and Traits: EEG, ERP, and Neuroimaging Studies

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Neuroelectric and imaging studies of meditation are reviewed. Electroencephalographic measures indicate an overall slowing subsequent to meditation, with theta and alpha activation related to proficiency of practice. Sensory evoked potential assessment of concentrative meditation yields amplitude and latency changes for some components and practices. Cognitive event-related potential evaluation of meditation implies that practice changes attentional allocation. Neuroimaging studies indicate increased regional cerebral blood flow measures during meditation. Taken together, meditation appears to reflect changes in anterior cingulate cortex and dorsolateral prefrontal areas. Neurophysiological meditative state and trait effects are variable but are beginning to demonstrate consistent outcomes for research and clinical applications. Psychological and clinical effects of meditation are summarized, integrated, and discussed with respect to neuroimaging data.

Keywords: meditation, EEG, ERP, fMRI

Overview and Definitions

Electroencephalographic (EEG) studies of meditative states have been conducted for almost 50 years, but no clear consensus about the underlying neurophysiological changes from meditation practice has emerged. Sensory evoked potential (EP) and cognitive event-related potential (ERP) assessments of meditative practice also reflect variegated results. Some reliable meditation-related EEG frequency effects for theta and alpha activity, as well as EEG coherence and ERP component changes, have been observed. Positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) studies are beginning to refine the neuroelectric data by suggesting possible neural loci for meditation effects, although how and where such practice may alter the central nervous system (CNS) have not yet been well characterized. The current study reviews and summarizes the neuroelectric results in conjunction with neuroimaging findings. Toward this end, meditation terms and effects are defined, the results of neuroelectric meditation studies are collated, and the findings are related to other neuroimaging reports.

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The word *meditation* is used to describe practices that self-regulate the body and mind, thereby affecting mental events by engaging a specific attentional set. These practices are a subset of those used to induce relaxation or altered states such as hypnosis, progressive relaxation, and trance-induction techniques (Vaitl et al., 2005). Given that regulation of attention is the central commonality across the many divergent methods (R. J. Davidson & Goleman, 1977), meditative styles can be usefully classified into two types—mindfulness and concentrative—depending on how the attentional processes are directed. Most meditative techniques lie somewhere on a continuum between the poles of these two general methods (Andresen, 2000; Shapiro & Walsh, 1984; B. A. Wallace, 1999). However, meditative traditions often do not characterize themselves according to this schema but rather place more emphasis on the benefits from the practice. Mindfulness practices involve allowing any thoughts, feelings, or sensations to arise while maintaining a specific attentional stance: awareness of the phenomenal field as an attentive and nonattached observer without judgment or analysis. Examples include Zen, Vipassana, and the Western adaptation to mindfulness meditation (Kabat-Zinn, 2003). Concentrative meditational techniques involve focusing on specific mental or sensory activity: a repeated sound, an imagined image, or specific body sensations such as the breath. Examples include forms of yogic meditation and the Buddhist Samatha meditation focus on the sensation of breath. Transcendental meditation (TM) fits somewhat within the concentrative forms, because practice centers on the repetition of a mantra, but the method places a primary emphasis on absence of concentrative effort and the development of a witnessing, thought-free “transcendental awareness.” The mantra is thought to eventually occupy awareness during meditative practice without concentrative effort, thereby possibly distinguishing the technique from other concentrative practices (Mahesh Yogi, 1963; Travis, Teece, Arenander, & Wallace, 2002). However, the development of a transcending observer’s perspective on their mental contents is an implicit or explicit goal of most meditative traditions (Goleman, 1996; Kabat-Zinn,

1990; Walsh, 1982). This distinction, if more thoroughly assessed across meditative traditions, might evolve as a second dimension for the state space into which different techniques could be categorized usefully.

Although these perspectives make it difficult to classify a given meditative practice as purely mindfulness or concentrative meditation, the two styles overlap in their approach toward similar goals. The former requires the maintenance of attention in a state of open perceptivity, and the latter requires narrowing of attentional focus. Mindfulness-based practices tend to encourage a continual return to an attentive set that is characterized by open, nonjudgmental awareness of the sensory and cognitive fields and include a meta-awareness or observation of the ongoing contents of thought. Concentrative techniques incorporate mindfulness by allowing other thoughts and sensations to arise and pass without clinging to them and bringing attention back to a specific object of concentrative awareness to develop an internal “witnessing observer.” Thus, the methods used to elicit specific states differ across practices, but the results similarly produce reported trait changes in self-experience: eliciting shift toward expanded experience of self not centered on the individual’s body schema and mental contents (Mahesh Yogi, 1963; Naranjo & Ornstein, 1971; Ornstein, 1972; Wallace, 1999; West, 1987).

An early theoretical model for understanding the neurophysiology of meditative states and traits used a continuum of autonomic arousal from parasympathetic (trophotropic) to sympathetic (ergotropic) dominance (Fischer, 1971; Gellhorn & Kiely, 1972). Mystical experiences of consciousness can be considered related to ergotropic states similar to those seen in psychiatric disturbance, ecstatic ritual, and hallucinogenic drug intoxication, but they also can be elicited through trophotropic meditative practice by means of a hypothetical rebound effect (Fischer, 1971). This framework has utility in reconciling the neurophysiological arousal of peak experiences in meditative states with the more commonly observed hypoarousal of meditative practice (J. M. Davidson, 1976). However, broad and encompassing statements about “the neurophysiology of meditation” are as yet unrealistic, because brain differences among meditative practices have not been well established (Dunn, Hartigan, & Mikulas, 1999; Lazar et al., 2003; Lehmann et al., 2001; Lou et al., 1999; Lutz, Greischar, Rawlings, Ricard, & Davidson, 2004). Some progress has been made to identify structure–function CNS relationships of meditative states and traits (Travis & Wallace, 1999); changes in arousal and attentional state involved in meditation are also related to hypnosis (Holroyd, 2003; Otani, 2003), drowsiness, sleep, and unconsciousness (Austin, 1998; Vaitl et al., 2005).

Meditation States and Traits

Measurement of the brain response to meditative practice is based on the premise that different conscious states are accompanied by different neurophysiological states and on reports that meditation practice induces distinct states and traits of consciousness. *State* refers to the altered sensory, cognitive, and self-referential awareness that can arise during meditation practice, whereas *trait* refers to the lasting changes in these dimensions that persist in the meditator irrespective of being actively engaged in meditation (Austin, 1998; Shapiro & Walsh, 1984; West, 1987).

Regular meditation practice can produce relatively short-term states as well as long-term changes in traits.

State changes from the meditative and religious traditions are reported to include a deep sense of calm peacefulness, a cessation or slowing of the mind’s internal dialogue, and experiences of perceptual clarity and conscious awareness merging completely with the object of meditation, regardless of whether a mantra, image, or the whole of phenomenal experience is the focal point (D. P. Brown, 1977; Wallace, 1999; West, 1987). A common experience of many meditative practices is a metacognitive shift in the relationship between thoughts and feelings; they come to be observed as arising phenomena instead of occupying full attention (Wallace, 1999; West, 1987). Also possible are “peak experiences,” characterized by blissful absorption into the current moment (e.g., Samadhi, nirvana, oneness); different traditions use specific names to describe the resulting ineffable states (Forman, 1990; Goleman, 1996; Mahesh Yogi, 1963; Wilber, 1977) that are affected by the extent of practice (Travis et al., 2002; Wallace, 1999). Although such peak–mystical states spurred the evolution of different meditation traditions, the practice is centered on trait effects (Dalai Lama & Cutler, 1998; Goleman, 1996, 2003; Kwon, Hahn, & Rhi, 1996), because peak experiences can occur under circumstances unrelated to meditation (James, 1902/1985; Maslow, 1964).

Trait changes from long-term meditation include a deepened sense of calmness, increased sense of comfort, heightened awareness of the sensory field, and a shift in the relationship to thoughts, feelings, and experience of self. States of awareness sometimes referred to as “the witness” or “transcendental experience” are also claimed to ensue over time. This experience consists of contentless awareness that is independent of mental activities, can be present during deep sleep, and produces the perception of an altered self-identity wherein the separation perceived between the observer and the observed grows ever fainter (Austin, 2000; Forman, 1990; Travis et al., 2002; West, 1987). As the perceived lack of separation develops, the sense of self seems to shift from mental thought centered in the body to an impersonal *beingness*. This awareness is related to the essential emptiness of a separate and isolated self-identity.

Studies to date have not been optimally designed to assess both meditation state and trait effects, in part because of the administrative challenge, difficulty in defining appropriate control groups and conditions, and complications arising from the synergistic association between meditative states and traits (Goleman, 1996; Travis, Arenander, & DuBois, 2004; Walsh, 1980; Wilber, 1977). Meditators consistently evince a witnessing awareness stance to their emotional and cognitive fields through their meditative practice and, therefore, cannot disengage this metacognitive shift. Hence, an observed state of meditation in a meditator may be a deeper reflection of the trait and may be observed in a meditator told to keep the mind busy with thoughts instead of meditating (Goleman, 1996; Mahesh Yogi, 1963). Moreover, nonmeditators simply cannot keep themselves in a state of physical immobility for the long lengths of time trained meditators can exhibit, making comparisons with the prolonged meditative state of a meditator practically impossible. Attempts to assess state versus trait effects have largely ignored these issues and used protocols that omit counterbalancing of meditation versus nonmeditation states, minimized the duration of nonmeditation simulations (Aftanas &

Golcheikine, 2002; Hebert & Lehmann, 1977; Kwon et al., 1996; Wallace, 1970), or only compared meditators and controls at rest to measure trait effects (R. J. Davidson et al., 2003; Travis et al., 2002; Travis, Tecce, & Guttman, 2000).

The developing field of neurophenomenology emphasizes the need to define the underlying neurophysiological correlates of conscious states and internal experience (Delacour, 1997; Gallagher, 1997; Jack & Roepstorff, 2002; Jack & Shallice, 2001; Lutz, Lachaux, Martinerie, & Varela, 2002; McIntosh, Fitzpatrick, & Friston, 2001; Varela, 1996). The goal is to use first-person reports to correlate internal experience with brain activity to guide neuroimaging analysis. For example, studies of TM states have begun to incorporate protocol methodology that marks the neurophysiological data with repeated reports from meditative participants to inform the neurophenomenological correlation (Mason et al., 1997; Travis, 2001; Travis & Pearson, 1999; Travis & Wallace, 1997); similar efforts are used for neuroimaging of hypnosis states (Rainville & Price, 2003). Collaborations between members of meditative traditions and neuroscientists have begun to distill the range of phenomenological changes from long-term contemplative practice (Goleman, 2003; Mason et al., 1997; Rapgay, Rinpoche, & Jessum, 2000; Travis et al., 2004). This approach is a necessary step to avoid the confound of meditation self-selection characteristics underlying the observed effects (Schuman, 1980; Shapiro & Walsh, 1984; West, 1980a), with trait measured using longitudinal prospective studies of meditative practice compared with non-meditating controls (R. J. Davidson et al., 2003).

One common parameter of internal experience secondary to meditative practices is the expansiveness in the experience of self, which includes agency, autobiographical memory referencing, and psychiatric or drug-induced changes in self-experience and depersonalization phenomena (Farrer et al., 2003; Farrer & Frith, 2002; Kircher & David, 2003; MacDonald & Paus, 2003; Mathew et al., 1999; Sierra, Lopera, Lambert, Phillips, & David, 2002; Simeon et al., 2000; Vollenweider, 1998; Vollenweider & Geyer, 2001; Vollenweider et al., 1997). However, neurophysiological studies of the altered self-experience from meditative practice are largely absent because of the difficulty in quantifying self-experience. Psychometric state and trait measures have been constructed (Dittrich, 1998; Friedman, 1983; Friedman & MacDonald, 1997; Vaitl et al., 2005), and some studies have begun use this approach to amplify meditation CNS findings (Lehmann et al., 2001; Travis et al., 2002, 2004).

EEG and Meditation

Continuous EEG

The EEG signal generated by alpha (8–12 Hz) activity was first described by Hans Berger in 1929, when he demonstrated that closing the eyes decreased sensory input and increased alpha power over the occipital scalp (Berger, 1929). EEG studies have used these methods to limn the neurophysiological changes that occur in meditation. Although the neuroelectric correlates of meditative altered consciousness states are not yet firmly established, the primary findings have implicated increases in theta and alpha band power and decreases in overall frequency (for reviews, see Andresen, 2000; J. M. Davidson, 1976; Delmonte, 1984b; Fenwick, 1987; Pagano & Warrenburg, 1983; Schuman, 1980; Sha-

piro, 1980; Shapiro & Walsh, 1984; Shimokochi, 1996; West, 1979, 1980a; Woolfolk, 1975).

The association between alpha changes and cortical activation has been assessed with combined EEG and fMRI-PET studies, with increased alpha power related to decreased blood flow in inferior frontal, cingulate, superior temporal, and occipital cortices (Goldman, Stern, Engel, & Cohen, 2002; Sadato et al., 1998). Stimulation of the sensory systems or by attentional focusing is associated with decreases in alpha power from the corresponding sensory area as well (Başar, Schürmann, Başar-Eroglu, & Karakaş, 1997; Niedermeyer & Lopes da Silva, 1999; Schürmann & Başar, 2001). Results suggest a positive correlation between thalamic activity and alpha power at some but not all locations (Schreckenberger et al., 2004). Although an integrated model of the neural generators for alpha and other frequencies has not yet been established (Başar, Başar-Eroglu, Karakaş, & Schürmann, 2001; Niedermeyer, 1997), alpha appears to be a dynamic signal with diverse properties that is sensitive to stimulus presentation and expectation (Schürmann & Başar, 2001; Steriade, 2000).

Table 1 summarizes the findings from EEG meditation studies. Alpha power increases are often observed when meditators are evaluated during meditating compared with control conditions (Aftanas & Golcheikine, 2001; Anand, Chhina, & Singh, 1961; Arambula, Peper, Kawakami, & Gibney, 2001; Banquet, 1973; Deepak, Manchanda, & Maheshwari, 1994; Dunn et al., 1999; Echenhofer, Coombs, & Samten, 1992; Ghista et al., 1976; Kamei et al., 2000; Kasamatsu & Hirai, 1966; Khare & Nigam, 2000; Lee et al., 1997; Litscher, Wenzel, Niederwieser, & Schwarz, 2001; Saletu, 1987; Taneli & Krahn, 1987; Wallace, 1970; Wallace, Benson, & Wilson, 1971; Wenger & Bagchi, 1961), and this band is stronger at rest in meditators compared with nonmeditator controls (Aftanas & Golcheikine, 2001, 2005; Corby, Roth, Zarccone, & Kopell, 1978; Deepak et al., 1994; Elson, Hauri, & Cunis, 1977; Kasamatsu & Hirai, 1966; Khare & Nigam, 2000; Satyanarayana, Rajeswari, Rani, Krishna, & Rao, 1992; Travis, 1991; Travis et al., 2002), suggesting that both state and trait alpha changes emerge from meditation practice (Delmonte, 1984a; Fenwick, 1987; West, 1980a). This outcome has been related to early biofeedback studies in which greater levels of alpha activity were found to be correlated with lower levels of anxiety and feelings of calm and positive affect (B. B. Brown, 1970a, 1970b; Hardt & Kamiya, 1978; Kamiya, 1969). However, subsequent reports suggested that the apparent increased alpha trait effect could be correlated with relaxation and selection bias for those who choose to meditate or stay with the practice, and not all meditation studies show an alpha state effect (Aftanas & Golcheikine, 2001; Benson, Malhotra, Goldman, Jacobs, & Hopkins, 1990; Drennen & O'Reilly, 1986; Hebert & Lehmann, 1977; G. D. Jacobs, Benson, & Friedman, 1996; Kwon et al., 1996; Pagano & Warrenburg, 1983; Schuman, 1980; Travis & Wallace, 1999). In sum, alpha power increases are associated with relaxation, which is observed in some individuals when meditating compared with baseline (Morse, Martin, Furst, & Dubin, 1977).

What is much less clear is whether and how meditation practices produce increased alpha beyond that obtained from reducing general arousal, which may become apparent only when fine-grained topographic mapping is combined with other neuroimaging methods. Studies using counterbalanced control relaxation conditions

(text continues on page 186)

Table 1
Summary of Meditation Studies Using Electroencephalographic (EEG) Methods

Study	Meditation type	N	Experimental design	Findings
Das & Gastaut (1957)	Kriya yoga	7	Advanced yogic meditators Rest → meditation → rest	State: alpha activity decrease, frequency increase; Samadhi with increased amplitude fast beta activity; no alpha blocking to stimuli; resting alpha with increased amplitude and wider distribution after meditation vs. before Trait: NA
Wenger & Bagchi (1961)	Yoga	14	Rest vs. meditation	State: Alpha activity increase, no alpha blocking Trait: NA
Anand et al. (1961)	Raj yoga	6	Rest vs. meditation	State: increased alpha power during Samadhi; no alpha blocking to visual, auditory, or painful stimuli during meditation Trait: high alpha amplitude at rest, beginners with higher alpha showed greater zeal to continue
Kasamatsu & Hirai (1966)	Zen	70	Meditators vs. controls EEG during eyes-open rest or meditation	State: increased alpha amplitude → decreased alpha frequency → alpha activity spreading frontally → theta bursts (→ alpha persists in eyes open rest state), nonhabituating alpha blocking Trait: increased alpha amplitude
R. K. Wallace (1970)	TM	15	Rest vs. meditation Some photic and auditory stimuli	State: decreased alpha frequency and increased in alpha amplitude; alpha blocking with no habituation Trait: NA
R. K. Wallace et al. (1971)	TM	36	Rest vs. meditation	State: increased alpha (8–10 Hz) amplitude, some participants with theta bursts Trait: NA
Banquet (1973)	TM	24	Rest vs. meditation, with repeated sessions Some photic and auditory stimuli	State: decreased alpha frequency → theta activity in some; deep meditation states with generalized fast frequencies at 20 and 40 Hz, persistent alpha activity after meditation, no alpha blocking, no statistics Trait: none reported
Williams & West (1975)	TM	19	Photic stimulation during rest	State: NA Trait: more early alpha induction, less alpha blocking during rest session; maintenance of low-arousal state without progression toward sleep
Younger et al. (1975)	TM	8	Meditation-4 sessions per participant	State: 40% in sleep Stages I or II (range 0–70%) Trait: NA
Tebecis (1975)	TM, self-hypnosis	42	Rest → meditation/self hypnosis, meditation/self-hypnosis → rest	State: none Trait: higher theta power in meditators and self-hypnosis
Pagano et al. (1976)	TM	5	Napping vs. meditation, 5 conditions per individual	State: 40% time in meditation met criteria for sleep Stages II–IV Trait: NA
Ghista et al. (1976)	Ananda Marga	5	Before, during, and after meditation	State: increases in alpha and theta power Trait: NA
Bennett & Trinder (1977)	TM	32	Meditators vs. controls, each participant had 2 analytic tasks and 2 spatial tasks; tasks and meditation-relaxation order counterbalanced	State: trend toward less variation in asymmetry during meditation compared with control relaxation; only alpha asymmetry assessed Trait: greater left asymmetry on analytical tasks, right asymmetry on spatial tasks
Hebert & Lehmann (1977)	TM	13	Meditators vs. controls	State: frontal-central theta bursts more common during meditation, associated with peaceful “drifting,” not drowsy Trait: more theta burst subjects (30% vs. 0%)
Morse et al. (1977)	TM, hypnosis, PR	48	Rest → meditation → rest Randomized order induction of various relaxation states	State: all relaxation methods induced equal alpha in some but not all participants Trait: none reported

(table continues)

Table 1 (continued)

Study	Meditation type	N	Experimental design	Findings
Fenwick et al. (1977)	TM		Rest → meditate → rest	State: theta bursts in some; meditation indistinguishable from stage-onset sleep; meditation appeared as drowsiness that does not descend to sleep as in rest periods Trait: NA
Elson et al. (1977)	Ananda Marga yoga	22	Rest → meditate → rest	State: nondescending alpha-theta (Stage I like) controls descend to Stage II during relaxation, increased alpha-theta in eyes-open rest after meditation; very advanced practitioner in nondescending alpha-theta with eyes open had highest theta Trait: higher alpha-theta power
Corby et al. (1978)	Ananda Marga yoga	30	LTM vs. STM vs. controls Rest → breath focus → mantra	State: theta power proportional to proficiency, experts with lowest percentage of sleep scores during meditation or relaxation Trait: higher theta and alpha power
Warrenburg et al. (1980)	TM, PR	27	LTM vs. PR vs. controls	State: none Trait: increased theta
Lehrer et al. (1980)	Passive meditation	32	Novices with 5 week passive meditation vs. PR vs. controls; tones	State: increased frontal alpha after auditory stimulation Trait: NA
Stigsby et al. (1981)	TM	26	Meditators vs. controls	State: decreased mean frequency in left frontal area, intra- and interhemispheric values stable, alpha-theta power for TM was between wakefulness and drowsiness and remained stable Trait: slower mean frequency in meditators (1 Hz)
Becker & Shapiro (1981)	TM, Zen, yoga	50	Different groups vs. attend and ignore controls	State: no effect of meditation on alpha blocking Trait: NA
Dillbeck & Bronson (1981)	TM	15	Beginning meditators, longitudinal study: 2 weeks of relaxation vs. 2 weeks TM	State: increase in frontal alpha coherence Trait: NA
Orme-Johnson & Haynes (1981)	TM	22	Meditators vs. controls at rest	State: NA Trait: increased alpha coherence
Farrow & Hebert (1982)	TM	1	Advanced TM meditator	State: increased alpha power and coherence during reported thought-free pure conscious experiences Trait: NA
Pagano & Warrenburg (1983)	TM	48	LTM vs. STM vs. PR practitioners vs. controls Rest → meditation → PR → rest	State: increased theta, decreased alpha, no hemispheric asymmetry Trait: increased theta in long-term practitioners
Persinger (1984)	TM	1	Case study	State: during TM practice peak experience accompanied by right temporal lobe delta wave-dominant seizure Trait: NA
Badawi et al. (1984)	TM	11	Meditation with subjective reports	State: thought-free respiratory suspension with increased delta, theta, alpha, and beta coherence; increased theta power Trait: NA
Dillbeck & Vesely (1986)	TM	22	EEG during a cognitive learning task	State: NA Trait: NA
Heide (1986)	TM	34	Meditators vs. controls Tones presented	Trait: Increased alpha coherence State: no changes in alpha blocking or habituation Trait: NA
Taneli & Krahne (1987)	TM	10	Repeated rest and meditation recordings, subjective reports	State: increased alpha amplitude Trait: NA
Saletu (1987)	TM	4	Experienced meditators Rest → meditation	State: increased alpha and theta power Trait: NA

Table 1 (continued)

Study	Meditation type	N	Experimental design	Findings
Ikemi (1988)	SRM	12	Before vs. during SRM vs. during drowsiness, novices	State: increased theta power, decreased beta power Trait: NA
J. Z. Zhang et al. (1988)	Qigong	32	LTM vs. STM vs. controls Rest → meditation	State: LTM increased alpha power frontally and decreased occipitally, decreased alpha frequency Trait: not reported
Gaylord et al. (1989)	TM	83	TM vs. PR vs. controls Longitudinal study, novices	State: increased alpha and theta coherence Trait: none
Jacobs & Lubar (1989)	Autogenic training	28	Longitudinal 7 weeks Relaxed listening to radio vs. autogenic training	State: with training increased theta power, increased theta power (35%), decreased alpha power (41%) Trait: none observed
Benson et al. (1990)	Tibetan Buddhist “gTum-mo” (heat generating)	3	Comparative study of rest meditation, stabilization meditation, g Tum-mo	State: increased beta activity, greater asymmetries (right sided), increased finger and toe temperature of up to 8.3 °C Trait: NA
Travis (1991)	TM	20	LTM vs. STM	State: NA Trait: increased alpha power and alpha coherence at rest
Satyanarayana et al. (1992)	Santhi Kriya yoga meditation	8	Before and after meditation on Training Days 1, 10, 20, 30	State: none Trait: increased occipital and prefrontal alpha power
Echenhofer et al. (1992)	Tibetan Buddhism	6	LTM vs. STM Meditation → rest	State: increased theta-alpha (6–12 Hz) power Trait: none reported
Deepak et al. (1994)	Mantra	20	Epileptic patients in 1-year clinical trial using EEG	State: patients, no effects, LTM increased alpha frequency Trait: increased alpha with decreased seizure frequency
Pan et al. (1994)	Concentrative vs. nonconcentrative Qigong	73	Two groups of Qigong meditators vs. controls, Rest → meditation	State: concentrative Qigong associated with increased frontal midline theta activity Trait: none reported
Jacobs et al. (1996)	Relaxation response (mantra based)	20	Novices guided meditation tape vs. listening to talk radio	State: decreased frontal beta power Trait: NA
Kwon et al. (1996)	Traditional Korean meditation	11	Rest → meditation → rest	State: variable; 6 participants with signs of drowsiness, 5 with highly individual patterns Trait: NA
Mason et al. (1997)	TM	31	LTM vs. STM vs. controls, sleep records	State: NA Trait: increased 6–10 Hz spectral power in Stage III–IV sleep with increased meditation and reports of awareness during sleep
Lee et al. (1997)	Qigong	13	Rest → meditation	State: increased alpha power Trait: NA
Travis & Wallace (1999)	TM	20	10-min rest and meditation counterbalanced order	State: increased intrahemispheric frontal-central and interhemispheric frontal alpha (8–10 Hz) coherence Trait: NA
Dunn et al. (1999)	Breath-focused Concentrative vs. Mindfulness	10	Relaxation and 2 meditation conditions counterbalanced, each practiced for 15 min	State: meditation vs. relaxation (increased beta and posterior alpha, decreased delta and theta power; mindfulness vs. concentrative meditation), increased anterior theta, central-posterior alpha, and beta power Trait: NA
Kamei et al. (2000)	Yoga	8	Rest → yoga with postures → yogic breathing → yogic meditation	State: increased alpha power and decreased serum cortisol, inverse correlation between alpha power and cortisol levels Trait: NA
Khare & Nigam (2000)	Yogic meditation, TM	40	Yogic vs. TM meditators vs. controls, rest → meditation	State: increased alpha power and coherence Trait: increased alpha power

(table continues)

Table 1 (continued)

Study	Meditation type	N	Experimental design	Findings
Arambula et al. (2001)	Kundalini yoga	1	Rest → meditation → rest	State: increased alpha power (P4-O2 electrodes) Trait: NA
Litscher et al. (2001)	Qigong	2	Qigong masters, meditation → mentally recite poem	State: increased alpha power Trait: NA
Travis (2001)	TM	30	Meditation with periodic bell rings eliciting subjective reports	State: increased theta-alpha (6–12 Hz) power and anterior-posterior coherence with pure conscious experiences Trait: NA
Lehmann et al. (2001)	Tibetan Buddhist practices	1	Five different meditative practices in succession for 2 min, with each repeated	State: different gamma (35–44 Hz) power increases associated with each practice Trait: NA
Travis et al. (2002)	TM	51	LTM vs. STM vs. controls recorded during cognitive task	State: NA Trait: increased theta-alpha (6–10 Hz) power and increased frontal coherence across all bands during cognitive CNV task
Aftanas & Golocheikine (2001, 2002, 2003)	Sahaja yoga	27	STM vs. LTM Rest → meditation	State: increased theta and alpha power (frontal-central), increased theta coherence, decreased dimensional complexity Trait: decreased alpha frequency, increased theta-alpha power
Davidson et al. (2003)	Mindfulness based stress reduction	32	Before and after meditation training intervention, EEG at rest and to emotional films	State: NA
Lutz et al. (2003)	Tibetan Buddhist	11	LTM vs. controls Rest → meditation → rest → meditation	Trait: leftward shift of frontal asymmetry State: increased gamma power, different gamma coherence patterns among practices
Hebert & Tan (2004)	TM	30	LTM vs. controls	Trait: none reported State: NA
Faber et al. (2004)	Zen	1	Repeated measures, 4 days with one control and 3 meditation scans	Trait: increase in anterior-posterior alpha coherence State: increased theta coherence, decreased gamma coherence except increased gamma coherence temporally
Lutz et al. (2004)	Tibetan Buddhist nonreferential love-compassion	18	LTM vs. controls Rest → meditation → rest → meditation	Trait: NA State: increased gamma power ratio, increased absolute gamma power, increased gamma synchrony
Murata et al. (2004)	Zen	22	Novice meditators	Trait: increased gamma power ratio correlated with length of meditative training State: increased frontal alpha coherence
Takahashi et al. (2005)	Zen	20	Novice meditators	Trait: NA State: increased frontal theta and low alpha
Aftanas & Golocheikine (2005)	Sahaja yoga	50	LTM vs. controls	Trait: NA State: NA Trait: increased theta and low alpha power at rest, decreased left hemispheric laterality in temporoparietal areas at rest, decreased induction of frontal gamma synchrony to aversive movie viewing

Note. NA = not applicable; TM = transcendental meditation; PR = progressive relaxation; LTM = long-term meditators; STM = short-term meditators; SRM = self-regulation method.

consistently have found a lack of alpha power increases or even decreases in a comparison of relaxation and meditation for both TM and yogic meditation (Corby et al., 1978; Hebert & Lehmann, 1977; G. D. Jacobs & Lubar, 1989; Lehrer, Schoicket, Carrington, & Woolfolk, 1980; Lehrer, Woolfolk, Rooney, McCann, & Carrington, 1983; Lou et al., 1999; Pagano & Warneburg, 1983; Tebecis, 1975; Travis & Wallace, 1999). How-

ever, some forms of meditation may affect alpha selectively, because a highly accomplished Kundalini yoga meditator was reported to produce a fivefold increase in alpha during meditative practice; only moderate increases in theta were found after the meditation period (Arambula et al., 2001). Further, advanced, but not beginner, Qigong meditators increased alpha power selectively over frontal cortex; decreases in alpha power over occipital cortex and

concomitant decreases in peak alpha frequency were observed (J. Z. Zhang, Li, & He, 1988).

Meditation appears to affect the EEG frequency distribution within the alpha band as both a state and a trait effect; a state-related alpha band slowing was observed in conjunction with increases in power (Banquet, 1973; Hirai, 1974; Kasamatsu & Hirai, 1966; Taneli & Krahné, 1987). A group of epileptics who were taught a yogic concentrative meditation and who were assessed at baseline and at 1 year demonstrated a decrease in the 1- to 8-Hz band and an increase in the 8- to 12-Hz band (Deepak et al., 1994). TM meditators produced an overall 1-Hz slower mean frequency relative to controls (Stigsby, Rodenberg, & Moth, 1981), and a 0.8-Hz trait-related alpha frequency difference between novices and long-term Sahaja yoga meditators of the same age was observed (Aftanas & Golocheikine, 2001).

A number of reports have suggested that increased theta (4–8 Hz) rather than increases in alpha power during meditation may be a specific state effect of meditative practice (Aftanas & Golocheikine, 2001, 2002; Anand et al., 1961; Banquet, 1973; Corby et al., 1978; Elson et al., 1977; Fenwick et al., 1977; Hebert & Lehmann, 1977; Hirai, 1974; G. D. Jacobs & Lubar, 1989; Pagano & Warrenburg, 1983; Travis et al., 2002; Wallace et al., 1971; Warrenburg, Pagano, Woods, & Hlastala, 1980). Some studies of yogic meditative practice found increases in theta to be associated with proficiency in meditative technique (Aftanas & Golocheikine, 2001; Corby et al., 1978; Elson et al., 1977; Kasamatsu & Hirai, 1966), and early investigations with Zen meditation indicate theta increases to be characteristic of only the more advanced practitioners (Kasamatsu & Hirai, 1966). Long-term meditators relative to nonmeditator controls exhibit trait higher theta and alpha power, perhaps related to the specific meditative technique and a slower baseline EEG frequency (Aftanas & Golocheikine, 2005; Andersen, 2000; J. M. Davidson, 1976; Delmonte, 1984a; Jevning, Wallace, & Beidebach, 1992; Schuman, 1980; West, 1979, 1980a; Woolfolk, 1975). However, self-selection effects cannot be ruled out, because EEG slowing is a typical finding for both state and trait meditation effects (Corby et al., 1978; Elson et al., 1977; J. Z. Zhang et al., 1988). In addition, there are some findings of alpha power decreases instead of increases for meditators (G. D. Jacobs & Lubar, 1989; Pagano & Warrenburg, 1983), with other suggestions of no systematic EEG change related to meditation state (Kwon et al., 1996; Tebecis, 1975; Travis & Wallace, 1999). This variability may stem from technical environments that impair relaxation or focus before or during a meditative session as well as participant–experimenter interactions and expectation influences during psychophysiological recordings (Cuthbert, Kristeller, Simons, Hodes, & Lang, 1981; Delmonte, 1985).

Theta power increases for meditative practice have been widely reported (Aftanas & Golocheikine, 2001; Ghista et al., 1976; Kasamatsu & Hirai, 1966; Kasamatsu et al., 1957; Lehmann et al., 2001; Lou et al., 1999; Pagano & Warrenburg, 1983; Schacter, 1977; Tebecis, 1975; R. K. Wallace, 1970; West, 1980b). Increased frontal midline theta power during meditation also has been observed (Aftanas & Golocheikine, 2002; Hebert & Lehmann, 1977; Kubota et al., 2001; Pan, Zhang, & Xia, 1994), although a similar activation occurs in non-meditation-related studies of sustained attention (Asada, Fukuda, Tsunoda, Yamaguchi, & Tonoike, 1999; Gevins, Smith, McEvoy, & Yu, 1997; Ishii et al., 1999; Mizuki, Tanaka, Isozaki, Nishijima, & Ianaga, 1980).

Attempting to relate the frontal midline theta to the concentrative aspect of meditative practices, Qigong practitioners of two different forms were assayed. One form of Qigong is a concentration-based practice, and the other is more mindfulness based (Pan et al., 1994). Even though the level of expertise in the two groups was equal, the concentrative Qigong technique produced frontal midline theta activity in practitioners, whereas the other more passive form did not. Although mindfulness-based practices have been assessed with EEG less often than concentrative practices, a comparative study found that mindfulness meditation produced greater frontal theta than concentrative meditation (Dunn et al., 1999). This is an odd outcome given the presumed association between frontal theta and focused concentration. Moreover, novice meditators were assessed, and global theta was shown to be higher during resting relaxation than either of the two meditative conditions, thereby implicating drowsiness as the source of the theta activity in this study.

Frontal midline theta activity is generated by anterior cingulate cortex, medial prefrontal cortex, or dorsolateral prefrontal cortex (Asada et al., 1999; Ishii et al., 1999). This activity is correlated with attention-demanding tasks (Gevins et al., 1997; Mizuki et al., 1980), and individuals exhibiting greater theta activity tend to have lower state and trait anxiety scores (Inanaga, 1998). Hence, increased frontal theta for both state and trait effects in meditation is associated with reported decreases in anxiety level resulting from practice (Shapiro, 1980; West, 1987), a finding that may be associated with the feelings of peace or blissfulness and low thought content that have been correlated with theta burst occurrence (Aftanas & Golocheikine, 2001; Hebert & Lehmann, 1977). Hypnotic states also appear associated with frontal midline theta and anterior cingulate cortex activation (Holroyd, 2003; Rainville, Duncan, Price, Carrier, & Bushnell, 1997; Rainville, Hofbauer, Bushnell, Duncan, & Price, 2002; Rainville et al., 1999), which has been observed during autonomic self-regulation as assessed by galvanic skin response biofeedback (Critchley, Melmed, Featherstone, Mathias, & Dolan, 2001, 2002). The scalp topography of the theta meditation effect is an important issue (e.g., Gevins et al., 1997), because most early reports used only a few parietal or occipital electrodes, so that claims for frontal midline theta may be unwarranted. Indeed, assessment of a relaxation-focused yogic nidra meditation with 16 electrodes found increases in theta power for all electrodes, suggesting that this type of practice may produce generalized rather than frontal-specific theta activity increases (Lou et al., 1999).

EEG coherence refers to the squared cross-correlation between EEG power from two scalp locations within a frequency band and indexes the functional covariation of activity among different cortical areas (Gevins, Bressler, et al., 1989; Gevins, Cutillo, et al., 1989; Nunez et al., 1997, 1999; Thatcher, Krause, & Hrybyk, 1986). Increased alpha–theta range coherence among recording sites has been observed intra- and interhemispherically for state effects during meditation (Aftanas & Golocheikine, 2001; Badawi, Wallace, Orme-Johnson, & Rouzere, 1984; Dillbeck & Bronson, 1981; Faber, Lehmann, Gianotti, Kaelin, & Pascual-Marqui, 2004; Farrow & Hebert, 1982; Gaylord, Orme-Johnson, & Travis, 1989; Hebert & Tan, 2004; Travis, 2001; Travis & Pearson, 1999; Travis & Wallace, 1999); similar trait effects were found in long-term meditators at rest or engaged in cognitive tasks (Dillbeck & Vesely, 1986; Hebert & Tan, 2004; Orme-Johnson & Haynes,

1981; Travis, 1991; Travis et al., 2002). Interpreting coherence requires consideration of methodological issues; false-positive results from different electrode configurations may color the interpretation of early coherence reports (Fenwick, 1987; Shaw, 1984).

EEG measures of phasic states during meditation have been described across studies, but the lack of a standardized phenomenological description compounds the problem: One mediator's ecstasy may not have much in common with another's pure conscious event, bliss, or absolute unitary being (d'Aquili & Newberg, 2000; Newberg et al., 2001). Some assessments of meditators in subjectively reported deep states of meditation found alpha desynchronization with fast beta rhythms predominant (Anand et al., 1961; Banquet, 1973; Das & Gastaut, 1955; Elson, 1979; Elson et al., 1977; Lo, Huang, & Chang, 2003). Other investigations have found increased activity in the temporal lobes for absorptive states of meditative ecstasy (Persinger, 1983, 1984). These activity patterns are similar to temporal lobe epilepsy and reports of profound ecstasy and spiritual, mystical, or religious experience from seizures (Asheim Hansen & Brodtkorb, 2003; Cirignotta, Todesco, & Lugaresi, 1980; Dewhurst & Beard, 1970; Foote-Smith & Smith, 1996; Persinger, 1993). Given the infrequent number of ecstatic states assayed, temporal involvement in peak experiences may occur, but the evidence is unclear.

Studies of TM have indicated increases of alpha coherence and respiratory suspension during episodes of thoughtless awareness or transcendent experiences (Badawi et al., 1984; Farrow & Hebert, 1982; Travis, 2001). A report of yogic meditation found respiratory suspension but no observable EEG changes for the experience of "near Samadhi" (Corby et al., 1978). These discrepancies may originate from the focus on affectively neutral pure consciousness events and thoughtless awareness as the main phenomenological correlate in the TM studies, whereas the assayed yogic states were characterized by blissful affect and unity of awareness (Travis & Pearson, 1999).

Although meditative practice can influence EEG measures, how meditation affects cognitive states and alters CNS traits is unclear. Some techniques may change alpha power as a trait effect toward the beginning of meditation training (Aftanas & Golocheikine, 2003; Deepak et al., 1994; Elson, 1979; Elson et al., 1977; Glueck & Stroebel, 1975; Khare & Nigam, 2000; Satyanarayana et al., 1992; Stigsby et al., 1981; Takahashi et al., 2005; Travis, 1991; Travis et al., 2002; Vassiliadis, 1973). Because baseline alpha levels equilibrate at higher power, theta power or theta-alpha coherence state effects might be manifested (Aftanas & Golocheikine, 2001; Corby et al., 1978; Travis & Wallace, 1999). A major limitation to date is the lack of sufficient topographic information, because most studies have used relatively few recording sites with little consistency of location (frontal, parietal, temporal, or occipital). Evaluation of different meditation techniques to characterize possible attentional and psychological set variation also is needed (R. J. Davidson & Goleman, 1977).

Lateralized EEG Measures

Following early theories of hemispheric specialization, the hypothesis developed that meditation practice was associated with right-hemispheric activity (Ornstein, 1972; West, 1987). State effects sometimes have been found: right-hemisphere relative to left-hemisphere decreases in alpha activity for meditators meditat-

ing compared with resting (Ehrlichman & Wiener, 1980; Fenwick, 1987). Trait effects were observed, suggesting that, compared with nonmeditators, meditators demonstrated greater lateralized EEG alpha for hemispheric analytical versus spatial discrimination tasks (Bennett & Trinder, 1977). Further, an assessment of lateralization trait differences in long-term Sahaja yoga meditators versus controls found no hemispheric lateralization in the meditator group and greater right- than left-hemispheric power over temporal and parietal cortices, suggesting relatively greater left-sided activation in the control group (Aftanas & Golocheikine, 2005). However, no general difference in hemispheric functioning has been found during meditation (Bennett & Trinder, 1977; Pagano & Warrenburg, 1983; Schuman, 1980). A randomized controlled trial involving an 8-week training course in mindfulness meditation produced increases in right-sided alpha power at baseline and in response to emotion-inducing stimuli, an effect that was strongest at the medial central (C3 and C4) lateral recording sites (R. J. Davidson et al., 2003). Antibody titers to a flu shot also increased in the meditation group relative to controls, and the titer increase correlated with the degree of leftward lateralization observed in hemispheric cortical activity (cf. Smith, 2004; Travis & Arenander, 2004).

These outcomes may reflect the relative activation of left and right prefrontal cortices, which indexes emotional tone and motivation such that greater left than right alpha power is associated with greater right frontal hemisphere activation (Coan & Allen, 2004; R. J. Davidson, 1988, 2003). In this framework, appetitive and approach-oriented emotional styles are characterized by a left-over-right prefrontal cortical activity, whereas avoidance and withdrawal-oriented styles are characterized by right-over-left prefrontal cortical dominance (R. J. Davidson, 1992; R. J. Davidson, Ekman, Saron, Senulis, & Friesen, 1990; R. J. Davidson & Irwin, 1999). Normal variation of positive versus negative affective states suggests left dominance for happier states and traits; left-over-right frontal hemispheric dominance is primarily related to the approach-withdrawal spectrum of emotion and motivation (R. J. Davidson, Jackson, & Kalin, 2000; Harmon-Jones, 2004; Harmon-Jones & Allen, 1998; Wheeler, Davidson, & Tomarken, 1993). In sum, meditation practice may alter the fundamental electrical balance between the cerebral hemispheres to modulate individual differences in affective experience; additional studies are warranted to assess this possibility.

Sleep and Meditation

After initial reports advocating a fourth state of consciousness originating from TM (R. K. Wallace, 1970; R. K. Wallace et al., 1971), several EEG meditation studies reported sleeplike stages during meditation with increased alpha and then theta power (Pagano, Rose, Stivers, & Warrenburg, 1976; Younger, Adriance, & Berger, 1975). Subsequent studies also seemed to suggest that meditation was a physiological twilight condition between waking and sleep, although this viewpoint did little to explain meditation state other than to indicate that it is not waking or sleeping as normally experienced (Fenwick et al., 1977; Williams & West, 1975). However, the ability to stay suspended between normal sleep and waking influenced meditation state assessment; EEG differences were found among meditation, baseline, and sleep (Corby et al., 1978; Elson et al., 1977; Stigsby et al., 1981;

Williams & West, 1975). These results contributed to the perspective that meditation training affects conscious awareness at a level similar to sleep Stage I, with marked increased alpha–theta power and a suspension of hypnagogic effects in a manner not reported by nonmeditators (Fenwick, 1987; Fenwick et al., 1977; Schuman, 1980; Stigsby et al., 1981; Tebecis, 1975; Young & Taylor, 1998). Meditators may stay suspended in a physiological state similar to the brief period of Stage I, in which theta predominates before transitioning to Stage II in normal individuals; such an explanation may account for increased theta levels observed in proficient meditators (Elson et al., 1977).

Early reports attempted to distinguish between meditative state and Stage I sleep by presenting auditory stimuli. It was found that during meditation theta desynchronization occurred, whereas during Stage I sleep alpha activity was induced (Banquet, 1973; Kasamatsu & Hirai, 1966). Differential EEG band patterns are observed in meditation compared with Stage I sleep: Meditation-related increases in theta are accompanied by stable or increased alpha power (Lou et al., 1999), whereas the increased theta power in sleep Stage I is accompanied by about a 50% decrease in alpha power (Rechtschaffen & Kales, 1968). Relative to relaxed but alert wakefulness, alpha coherence decreases are observed in drowsiness (Cantero, Atienza, Salas, & Gomez, 1999). In contrast, increases in theta and alpha coherence above baseline resting wakefulness are commonly found during meditation, further dissociating meditation from drowsiness and early sleep stages (Aftanas & Golcheikine, 2003; Faber et al., 2004; Travis, 1991; Travis et al., 2002; Travis & Wallace, 1999). Increases in overall cerebral blood flow during meditation have been observed, whereas decreases are characteristic of sleep (Jevning, Anand, Biedebach, & Fernando, 1996). This outcome may be related to findings of increased melatonin levels in meditators at baseline and increased levels in meditators during sleep on nights after meditating (Harinath et al., 2004; Solberg et al., 2004; Tooley, Armstrong, Norman, & Sali, 2000). These results support subjective reports that meditation and sleep are not equivalent states (Aftanas & Golcheikine, 2001; Banquet & Sailhan, 1974; Corby et al., 1978; Delmonte, 1984b; Hebert & Lehmann, 1977; Ikemi, 1988; Naveen & Telles, 2003; Paty, Brenot, Tignol, & Bourgeois, 1978; Stigsby et al., 1981).

The effects of meditation on sleep also have been assessed. An early study comparing sleep in TM meditators with controls reported higher levels of alpha activity for the meditators during sleep Stages III and IV (Banquet & Sailhan, 1974). Accomplished TM meditators who reported maintaining witnessing awareness throughout their sleep cycles demonstrated greater amounts of fast theta and slow alpha (6–10 Hz) power during sleep Stages III and IV (when such activity is at a minimum) relative to controls. Long-term meditators not reporting awareness throughout the sleep cycle also exhibited increased theta and alpha activity during deep sleep but of smaller amplitude (Mason et al., 1997). These findings have been hypothesized to reflect the development of a transcendental consciousness that persists during waking, dreaming, and deep sleep. Meditation experience may, therefore, produce neurophysiological changes during sleep that correspond to a progression along a continuum from being totally unconscious to totally conscious during deep sleep (Varela, 1997).

Alpha Blocking and Alpha Habituation

An initial conceptualization of meditation effects proposed that deautomatization was induced, such that each stimulus occurrence was perceived as fresh under mindfulness, open-awareness meditative states relative to rest conditions (Deikman, 1966; Kasamatsu & Hirai, 1966). A possible measure of this process is EEG alpha blocking, which is defined as a decrease in ongoing alpha (8–12 Hz) power when comparing prestimulus to poststimulus activity. Prototypical alpha blocking occurs when alpha power is reduced after closed eyes are opened and is most pronounced in the occipital cortex, reflecting the association between alpha activity and decreases in cortical processing (Başar et al., 1997; Niedermeyer, 1997). Alpha blocking also is observed when a series of discrete stimuli are presented, such that small alpha power decreases are obtained between pre- and poststimulus alpha activity. This effect habituates over the course of a stimulus train after 10 to 20 stimuli, and an absence of alpha decrement from stimulus presentations is typical (Barlow, 1985; Morrell, 1966). In addition, increased alpha activity is induced when normal individuals are aroused from drowsiness or sleep by stimuli (Niedermeyer, 1997).

Field recordings of meditating Indian yogis found no alpha blocking in response to both auditory and physical stimuli such as hands placed into ice water (Anand et al., 1961; Das & Gastaut, 1957; Wenger & Bagchi, 1961). However, subsequent studies of Japanese Zen monks reported alpha blocking to auditory stimuli that did not habituate (Hirai, 1974; Kasamatsu & Hirai, 1966). Similar early studies of TM practitioners while meditating yielded conflicting results; one found an absence of alpha blocking, and another indicated that most participants demonstrated no alpha-blocking habituation to auditory stimuli (Banquet, 1973; R. K. Wallace, 1970). Both Zen and TM meditators, however, produced theta activity during meditation that was associated with states of consciousness different than those observed for drowsiness, because auditory stimuli produced a general EEG desynchronization compared with the alpha induction found in drowsy nonmeditator controls (Blake & Gerard, 1937; Morrell, 1966). These early findings suggest that specific meditation practices might produce EEG measures that reflect baseline levels, stimulus reactivity, and brain state differences.

EEG studies of meditation in response to stimuli have attempted to characterize state and trait effects for alpha reactivity. Long-term TM meditators were instructed to “just rest” with eyes closed as photic stimulator light flashes were presented (Williams & West, 1975). The major findings for meditators compared with controls were as follows: (a) Alpha activity during the prestimulus interval was greater, (b) alpha induction occurred earlier with more regularity, and (c) alpha blocking continued throughout the stimulus train (i.e., less habituation was observed). These results suggested that the TM individuals in a resting state demonstrated substantially less EEG shifting along the wake–drowsy continuum. A subsequent study assessed TM, Zen, and yoga mantra meditation techniques in advanced practitioners; separate non-meditator “attend” and “ignore” control groups were included (Becker & Shapiro, 1981). The attend group was told to “pay strong attention” to each click, notice all of its sound qualities and subtleties, and count the number of clicks; the ignore group was told to “try not to let the clicks disturb your relaxed state.” Pre- and poststimulus amplitude measures indicated comparable alpha

blocking and habituation among groups. Another study of TM meditators likewise found no effects of meditation on alpha blocking (Heide, 1986). Thus, comparison of well-defined meditating and appropriate nonmeditating controls failed to produce the previously reported findings on alpha blocking and habituation to auditory stimuli.

Variation in meditation experience, recording environments, and methodological details may have contributed to the differences between the initial field and later laboratory findings. The early studies demonstrated that yogic (toward the extreme of concentrative-based) practice was characterized by the absence of alpha blocking and Zen (toward the extreme of mindfulness-based) practice was characterized by a lack of alpha-blocking habituation. These outcomes are consistent with the reported subjective states of being deeply immersed and removed from sensory experience during yogic practices, even while being more present to the ongoing moment-to-moment sensory experiences during Zen. Hence, literature reviews that highlight different meditative techniques have accepted the differential effects for the two techniques as fact (Andresen, 2000; Jevning et al., 1992; West, 1980a; Woolfolk, 1975). The lack of replication for these effects may reflect an absence of adequate control conditions or the challenge in finding sufficiently trained meditators (Becker & Shapiro, 1981).

Additional early meditation studies have shown relatively increased alpha power after aversive stimuli. Comparison of meditation intervention and a progressive relaxation training intervention in controls found greater frontal alpha power in response to loud stimuli for the meditation group (Lehrer et al., 1980). In experiments with affectively arousing name calling, highly experienced Zen practitioners showed no alpha blocking (Kinoshita, 1975). Subsequent assessment of highly experienced Tibetan Buddhist monks indicated that dramatically reduced alpha blocking could occur, because an accomplished monk engaged in an open-awareness meditative technique yielded a complete lack of startle response, a finding consistent with a possible underlying lack of alpha blocking (Goleman, 2003). In sum, the effects of different meditative practices and induced states on EEG alpha responsiveness to stimuli are still unclear with respect to both state and trait effects.

Advanced EEG Meditation Studies

Specificity of neuroelectric measures in meditation has been increased by assessment of EEG coherency and high-frequency gamma band (30–80 Hz) in attempts to characterize mechanisms of conscious awareness and perceptual binding (Croft, Williams, Haenschel, & Gruzelier, 2002; Engel & Singer, 2001; Llinas & Ribary, 1993; Meador, Ray, Echauz, Loring, & Vachtsevanos, 2002; Rodriguez et al., 1999; Sauve, 1999; Sowards & Sowards, 2001; Uchida et al., 2000). The low-resolution electromagnetic tomography algorithm (LORETA) of EEG signals selects the smoothest of all possible three-dimensional current distributions to localize scalp signals in a manner compatible with fMRI localization obtained in conjunction with simultaneous EEG and intracranial measurements (Lantz et al., 1997; Pascual-Marqui, Michel, & Lehmann, 1994; Vitacco, Brandeis, Pascual-Marqui, & Martin, 2002). A single highly experienced meditation teacher was evaluated using LORETA across four meditative states—visualization, mantra, self-dissolution, and self-reconstruction—in a case study

with repeated elicitation of the meditative states but no resting condition (Lehmann et al., 2001). Gamma activity was the only band demonstrating differential spatial distributions for the various meditations; gamma power increased during the visualization and verbalization meditations in the right posterior occipital and left central-temporal regions, respectively. Increased gamma activity also was observed during the self-dissolution meditation in the right superior frontal gyrus, a brain area linked to an altered sense of self from cannabinoid-induced depersonalization and cognitive self-detachment from lesions (Mathew et al., 1999; B. L. Miller et al., 2001). These findings are consistent with right frontal involvement in the experience of agency, self-awareness, and self-referenced memory (Keenan, Nelson, O'Connor, & Pascual-Leone, 2001; Keenan, Wheeler, Gallup, & Pascual-Leone, 2000; Wheeler, Stuss, & Tulving, 1997).

Highly experienced Tibetan Buddhist meditators and novices who practiced the method for just 1 week were compared while engaged in three separate techniques: one-pointed concentration on an object, attention without object, and a state of nonreferential love and compassion (Lutz et al., 2004; Lutz, Greischar, Ricard, & Davidson, 2003). Large increases in 40-Hz gamma power were recorded in the meditators for the meditative state compared with the rest state. Different synchrony patterns between the two groups and among the meditative states were observed that imply changes in both state and trait effects in the gamma band. Another study of advanced Tibetan Buddhist meditators using ambiguous bistable visual stimuli found different effects for concentrative compared with compassion meditation, thereby supporting the idea that these forms of practice lead to distinct mind-brain states (Carter et al., 2005). For the nonreferential love state, some meditators demonstrated greater average gamma power over frontal areas during meditation than alpha power; an absence of similar spectral changes was found in the nonmeditator controls. Further, the ratio of gamma to theta power was larger in the meditators at baseline; increases were observed during the meditative practice. A significant increase in gamma synchrony also was found in the meditator but not the control group during meditation. These findings indicate that, at least for meditative practices involving affective regulation, gamma activity may play a prominent role.

Sahaja yoga meditators, who practiced daily for 5 years, were compared with a group with less than 6 months experience (Aftanas & Golocheikine, 2001, 2002, 2003). The long-term meditators relative to novices exhibited slower mean frequency and greater theta-alpha power at rest, widespread increases in theta and early alpha power, and enhanced theta coherence at frontal-central locations. Theta coherence was most pronounced in the left frontal pole, and the theta power increases correlated positively with self-reported blissful affect and negatively with thought appearance rates. As EEG frequencies for long-term meditators were slowed, alpha frequency was defined individually with early alpha at 5.6 to 7.5 Hz, which most previous studies would have attributed to theta activity. To date, this is the only meditation study to define individual alpha frequencies before analysis, and the results may help account for the variegated previous findings. Decreased chaotic dimensional complexity over midline frontal and central cortical regions also was observed and may reflect decreased information processing mediated by frontal midline theta exerting an inhibitory influence on the normally automatic processing of association cortices. A related report assessing trait effects found that

long-term Sahaja yoga meditators differed from controls in their lack of frontal gamma power increases to emotionally aversive movie clips (Aftanas & Golocheikine, 2005). These findings are intriguing because it has long been claimed that one of the primary benefits from meditative training is greater emotional stability for challenging life events (Kabat-Zinn, 1990).

Conclusions From EEG Meditation Studies

It is difficult to draw specific inferences from these studies other than the fact that theta and alpha band activity seems affected by meditation (state), which may alter the long-term neuroelectric profile (trait). The effects suggest that meditation practice is related to increased power in theta and alpha bands and decreased frequency at least in the alpha band, with overall slowing and alteration of coherence and gamma effects. Several factors could contribute to the observed variability. First, the word *meditation* includes many different techniques, and the specific practices may lead to different state and trait changes. Second, within a specific meditation tradition, individuals can vary in their degree of meditative practice, and their self-selection for participating in EEG studies could affect state and especially trait measurement outcome; that is, how constitutional variables such as affective valence, introversion versus extroversion, and anxiety level affect these measures is unknown. Third, neurophysiological markers of meditative states could alter baseline EEG patterns, such that clear

within-group meditation effects are obscured (e.g., overall large spectral power would mask pre- versus postmeditation state changes). Fourth, how EEG measures might be affected by meditator age has not been determined despite the neuroelectric changes that occur from early to middle age adulthood in humans (Polich, 1997). Fifth, methodological difficulties limit the generalizability of early recordings and analysis, especially when stimuli were used to elicit different alpha activity levels.

ERPs and Meditation

Figure 1 schematically illustrates brain potentials that can be elicited after a stimulus is presented. EPs are evoked automatically with repetitive sensory stimulation, whereas ERPs are elicited with cognitive task processing (Hall, 1992; Picton & Hillyard, 1974; Picton, Hillyard, Krausz, & Galambos, 1974). Auditory stimuli produce the auditory brainstem response and middle latency response. The longer latency auditory ERPs are thought to reflect the activation of primary auditory cortex (Polich & Starr, 1983; Wood & Wolpaw, 1982). Visual and somatosensory EPs also can be evoked; standard clinical procedures are now well defined (Chiappa, 1996). The P300 component is usually elicited by assigning individuals a stimulus discrimination task and can be obtained across modalities (Donchin, 1981; Johnson, 1988; Picton, 1992; Polich, 2003, 2004).

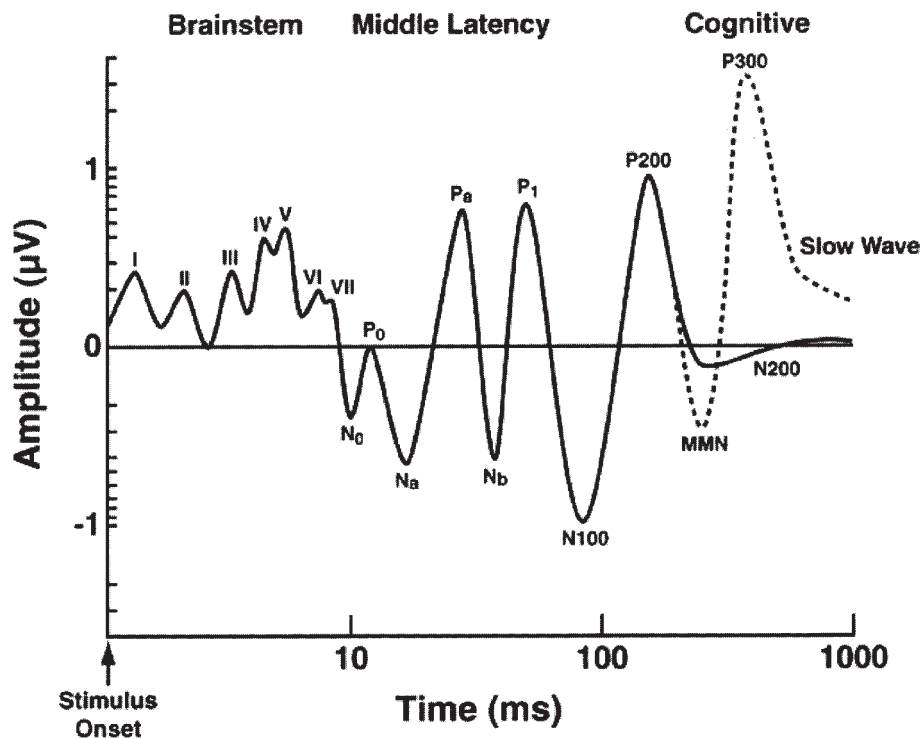


Figure 1. Schematic illustration of evoked and event-related brain potentials from auditory stimuli. Logarithmic scales for amplitude and latency are used for illustrative purposes only. MMN = Mismatch Negativity. From "Human Auditory Evoked Potentials: I. Evaluation of Components," by T. W. Picton, S. A. Hillyard, H. I. Drausz, and R. Galambos, 1974, *Electroencephalography and Clinical Neurophysiology*, 36, p. 181. Copyright 1974 by Elsevier Scientific Publishing Company. Adapted with permission.

Table 2
Summary of Meditation Studies Using Evoked Potential (EP) or Event-Related Potential (ERP) Methods

Study	Meditation type	N	Experimental design	EP/ERPs	Findings
Paty et al. (1978)	TM	25	Meditators vs. controls, before vs. after meditation/relaxation	CNV	State: increased CNV amplitude after meditation, decreased amplitude after sleeplike relaxation control period Trait: NA
Barwood et al. (1978)	TM	8	Before, during, and after meditation; sleeping	AEP	State: nonsignificant decrease in N1 latency during meditation Trait: NA
Corby et al. (1978)	Tantric yoga Ananda Marga	30	LTM vs. STM vs. controls, before vs. breath-focused vs. mantra meditation	EEG, passive auditory oddball task	State: no findings; all groups showed equivalent decreases in component amplitudes across sessions Trait: NA
Banquet & Lesévre (1980)	Yoga	20	Meditators vs. controls, before vs. after meditation or rest	Visual oddball task	State: after meditation, increased P300 amplitude; after rest, decreased P300 amplitude Trait: shorter RT, fewer mistakes, increased N120 and P200 amplitudes
McEvoy et al. (1980)	TM-Siddhi	5	Meditators vs. controls, before vs. after meditation	ABR	State: Wave V latency increased at 45–50 dB and decreased at 60–70 dB; intensity-latency relationship increased in slope from 45–70 dB, central transmission time (Wave V-Wave I) increased at 50 dB Trait: NA
Becker & Shapiro (1981)	TM, Zen, yoga	50	Different meditation groups; attend and ignore control groups	AEP and EEG	State: AEP, no effect of meditation on average N1, P2, P3, early larger N1 amplitude that habituated to the mean in yoga and TM groups Trait: NA
Ikemi (1988)	SRM	12	Before vs. during SRM vs. during drowsiness, beginning meditators	CNV	State: during SRM, decreased CNV amplitude, error rate; during drowsiness, decreased CNV amplitude, increased RT, error rate Trait: NA
Goddard (1989)	TM	26	Elderly meditators vs. elderly controls	Auditory and visual oddball task	State: NA Trait: visual P300 latencies shorter in meditators, no auditory P300 effects
Liu et al. (1990)	Qigong	21	Before, during, and after meditation	ABR, MLR, AEP	State: ABR Waves I-V amplitudes increased, MLR Na-Pa amplitude decrease; AEP P2 amplitude decrease Trait: NA
Cranson et al. (1990)	TM	39	LTM vs. STM vs. controls	Auditory oddball task	State: NA Trait: P300 latency inversely correlated with length of meditation practice: none > short > long
Goddard (1992)	TM	32	Elderly meditators vs. elderly controls vs. young meditators vs. young controls	Visual oddball task	State: NA Trait: P300 latencies longer in elderly than young; elderly meditators vs. elderly controls had shorter P300 latencies and longer RTs; dissociation of P300 latency and RT
Gordeev et al. (1992)	Yogic	29	Meditators vs. controls	VEPs, SEP	State: amplitude of intermediate and late components of VEPs and SEPs diminished 2–4 fold; SEP early components decreased in amplitude in hemisphere ipsilateral to stimulation only Trait: none reported

Table 2 (continued)

Study	Meditation type	N	Experimental design	EP/ERPs	Findings
Telles & Desiraju (1993)	<i>Om</i> mantra meditation	14	Meditators vs. controls, before vs. during meditation technique	MLR	State: NA Trait: Nb latency decrease in meditator group but no effect seen in controls, small effect size
W. Zhang et al. (1993)	2 types of Qigong	48	Two groups of LTM vs. STM vs. controls	Flash VEP	State: VEP amplitude increase in one form of Qigong and decreased in the other Trait: NA
Telles et al. (1994)	<i>Om</i> mantra meditation	18	Meditators vs. controls, baseline vs. <i>om</i> meditation vs. <i>one</i> meditation	MLR	State: Na amplitude increased in meditators and decreased in nonmeditators during <i>om</i> ; Na amplitude decreased in meditators during <i>one</i> Trait: NA
Travis & Miskov (1994)	TM	11	Before vs. after meditation vs. after rest	Auditory oddball task	State: decreased latency P300 after TM but not rest; trend toward higher amplitude P300 after TM Trait: NA
Murthy et al. (1997, 1998)	Kriya yoga, 3-month training	45	Patients: depressed vs. dysthymic vs. controls	Auditory oddball task	State: NA Trait: improvement in depressive symptoms and increase of P300 amplitude in novice meditators; effect perhaps from arousal due to alleviation of depression
Panjwani et al. (2000)	Sahaja yoga	34	Epilepsy patients: yoga group vs. sham yoga group vs. controls	ABR, MLR, VCS	State: NA Trait: ABR, no effects; MLR, increased Na-Pa amplitude at 6 months in meditation group, VCS increased
Travis et al. (2000)	TM	41	Three groups varying in TM experience, frequency of transcendent experiences	CNV, simple; CNV, distraction task	State: NA Trait: CNV amplitude proportional to TM practice and frequency of transcendent experiences; distraction effects (decreases in CNV amplitude) inversely proportional to frequency of transcendent experiences
Travis et al. (2002)	TM	51	LTM vs. STM vs. control CNV, simple CNV, choice task	State: NA	Trait: simple CNV amplitude proportional-choice CNV amplitude inversely proportional to frequency of transcendent experiences and TM practice

Note. TM = transcendental meditation; CNV = contingent negative variation; NA = not applicable; AEP = auditory evoked potential (long latency); LTM = long-term meditators; STM = short-term meditators; EEG = electroencephalographic; RT = response time; ABR = auditory brain stem response; SRM = self-regulation method; MLR = middle latency response; VEP = visual evoked potential (flash stimulus); SEP = somatosensory evoked potential; VCS = visual contrast sensitivity.

Table 2 summarizes the major EP and ERP meditation studies. The meditation effects are reviewed next for the sensory and cognitive domains. A summary of studies using contingent negative variation (CNV) is then presented. The rationale for these investigations is derived from the early EEG studies outlined previously. Meditators sometimes produced altered amplitudes and

shorter potential latencies when stimuli were presented and EEG was recorded, thereby suggesting increased attentional control and CNS quiescence (Banquet & Lesévre, 1980). This interpretation is consonant with results from the 1970s in normal individuals that selective attention and later cognitive processing were reflected by different ERP components. Advanced concentrative meditation

practitioners seemed to demonstrate decreased amplitude and latency for several sensory EPs (e.g., Anand et al., 1961; Gordeev, Baziian, & Liubimov, 1992), whereas mindfulness-based practices sometimes induced a decrease in habituation (e.g., Banquet, 1973; Kasamatsu & Hirai, 1966). Thus, these methods were used to characterize sensory and cognitive information processing in meditation as has been done with behavioral measures indicating enhanced perceptual acuity (D. P. Brown, Forte, & Dysart, 1984a, 1984b; Panjwani et al., 2000).

Auditory Stimulus Potentials

Brainstem potentials. Auditory brainstem responses occur within 10 ms after stimulus presentation and reflect initial sensory processing. Assuming that meditation practice affects attentional mechanisms, these potentials should not be influenced by either meditation state or trait. Auditory brainstem responses were obtained from practitioners of TM–Siddhi meditation supposed to augment normal hearing by using attention to special mantras constructed to sensitize the auditory system and lead to awareness of subtle inner sounds not normally perceived (Mahesh Yogi, 1963; McEvoy, Frumkin, & Harkins, 1980). Binaural click stimuli were presented at 5 to 70 dB in different conditions to elicit auditory brainstem responses before and after meditation. As stimulus intensity increased, Wave V latencies were differentially affected by meditation. At threshold intensities of 45 to 50 dB, Wave V latency increased, whereas at intensities of 65–70 dB latencies decreased relative to baseline, thereby leading to an increased intensity–latency relationship between 45 and 70 dB after meditation. Wave V–I latency differences (central transmission time) also increased after meditation for 50 dB but not other intensities. Background noise is 40 to 50 dB, so that meditation may attenuate the sensitivity to these intensities, thereby enhancing sounds at threshold (5–40 dB) and speech (60–70 dB) intensity levels.

Middle latency potentials. Middle latency response potentials are generated post-brain stem and reflect initial cortical auditory processing occurring between 10 and 80 ms. Recordings of meditators using the traditional mantra *om* were made before and during meditation; a nonmeditator control group was comparably assessed while resting quietly at two different times (Telles & Desiraju, 1993). The meditators produced a small but reliable decrease in Nb component latency after meditating relative to the preceding rest period, whereas for the control group no changes were found. In a subsequent study involving novice and expert mantra meditators, Telles, Nagarathna, Nagendra, and Desiraju (1994) compared middle latency response measures before and after meditating on the syllable *om* versus the word *one*. Novice meditators demonstrated a decrease in Na amplitude in the *om* condition; expert meditators demonstrated an increase in Na amplitude for the *om* condition but an amplitude decrease for the *one* condition. Brahmakumaris Raja yoga meditators were assessed before and during meditation; a decrease in Na peak latency was found (Telles & Naveen, 2004). The Na potential is thought to be generated at the midbrain–thalamic level, so that concentrative mantra meditation may affect early thalamic sensory processes.

Sahaja yoga emphasizes adopting the witness posture toward thoughts instead of flowing with them during meditation and is, therefore, very close to the mindfulness end of the meditational spectrum. This method was assessed in three groups of young adult

epileptic patients (Panjwani et al., 2000). One group practiced Sahaja meditation, another group sat quietly in sham meditation, and a control patient group had no meditation instruction. Auditory brainstem response and middle latency response measures were obtained before the meditation intervention and again 3 months and 6 months later. No auditory brainstem response effects were obtained, but the Sahaja yoga group demonstrated an increase in middle latency response Na–Pa amplitude at 6 months. Although Sahaja yoga meditation in normal controls was not assessed, this outcome also suggests the influence of meditation on initial cortical auditory processing.

Qigong is a distinct meditation technique that emphasizes becoming aware of the *Qi* or subtle energy in the body, and consciously manipulating it by means of intentionality, physical postures, and movements (McCaffrey & Fowler, 2003). Several different types of brain potentials were observed before, during, and after a Qigong meditation session in a within-subject design (Liu, Cui, Li, & Huang, 1990). Auditory brainstem response Waves I through V increased in amplitude 55% to 76%, whereas middle latency response Na and Pa amplitudes decreased 50% to 73% during Qigong meditation relative to the before and after conditions. The authors hypothesize that the brainstem may be synergistically released from descending inhibition to produce the auditory brainstem response amplitude increase when the initial cortical activity indexed by middle latency response potentials decreases during meditation.

Long latency potentials. TM meditators presented with auditory tones (1/s) demonstrated decreased P1, N1, P2, and N2 component latencies for meditators at baseline and meditation–rest states compared with nonmeditator control group values (Wandhofer, Kobal, & Plattig, 1976). Another study used 50 tones (1-s duration) presented in three blocks to TM meditators before, during, and after meditation in a within-subject design; additional recordings were made during sleep. Although N1 latency was longer in the before control condition relative to the meditation condition, this effect was unreliable, and no other condition differences were found for any of the auditory long-latency potential components (Barwood, Empson, Lister, & Tilley, 1978).

Ananda Marga meditative practice focuses initially on withdrawing from external orientation by means of breath-focused concentration, which is then followed by mantra meditation and, therefore, lies toward the concentrative meditation end of the spectrum. Experienced meditators were compared with novice meditators and nonmeditating controls (Corby et al., 1978). Each individual was exposed to a series of tones presented at a rate of 1/s for 20 min, with the inclusion of an oddball tone (1/15) in each of three conditions: baseline rest, breath-focused awareness, and mantra meditation. Nonmeditating controls mentally repeated a randomly chosen two-syllable word; all groups were instructed to ignore the tones. For the experienced meditators compared with other subjects, EEG theta and alpha power was higher in both the baseline and meditative conditions. For all three groups, infrequent tones elicited smaller N1 amplitudes and a positive potential occurring at approximately 250 ms (dubbed “P2-3” but likely a P2). Auditory long-latency potential components during the baseline rest were similar to the meditation conditions for both tones, but during meditation P2-3 amplitude decreased for infrequent tones and increased for frequent tones. Condition order was not counterbalanced, so it is likely that habituation effects produced

the amplitude decrements. The reason for the P2-3 amplitude increase to the frequent tones is unclear.

Auditory long-latency potentials were obtained from five groups of participants—Zen, TM, yoga, and two groups of nonmeditator controls—who were instructed either to attend or ignore loud click stimuli (115 dB) presented at 15-s intervals (Becker & Shapiro, 1981). As noted, no differential alpha blocking was found among the five groups when meditators meditated and controls applied their instructed attentional focus at rest. No auditory long-latency potential components demonstrated any differences other than the production of larger passive P300 amplitudes in the attend group as observed previously (Becker & Shapiro, 1980). N100 amplitude for the TM and yoga meditation participants was increased over the first 30 stimulus presentations and then reduced to the same size as the other groups after 40 to 50 stimulus presentations. The authors suggested that, given the mantras used by both groups, the attentional state of the TM and yoga meditators may have been attuned to inner sounds, which could have contributed to a greater sensitivity for the auditory stimulus input, even above that of the control attend group specifically instructed to pay full attention to the auditory input.

Qigong meditators were assessed by presenting 10-ms tones and recording before, during, and after a 30-min Qigong meditation session (Liu et al., 1990). P200 amplitude decreased 44% from the baseline to the meditation state and returned to baseline after meditation. This outcome suggests that later auditory long-latency potential measures may be sensitive to meditation state.

Auditory P300. TM practice was studied using a passive auditory paradigm listening study with variable interstimulus intervals (1–4 s) between identical tone stimuli (Cranson, Goddard, & Orme-Johnson, 1990). The participants were nonmeditator controls, novice, and highly experienced TM meditators (mean age = 20, 28, and 41 years, respectively). IQ scores did not differ among the groups. Passive P300 potential latency was shorter for the two meditation groups; the long-term meditators showed the shortest P300 latency regardless of age (cf. Polich, 1996). These results imply that auditory long-latency potentials might reflect meditation trait differences.

An auditory oddball task was used with eyes closed to assess experienced TM meditators at pretest baseline, after 10 min of rest, and after 10 min of TM practice; conditions were counterbalanced across participants (Travis & Miskov, 1994). P300 latency decreased at Pz after TM practice relative to no change after the rest condition. Sudarshan Kriya yoga is a meditation system that emphasizes breathing techniques. This technique was used as an intervention to assess dysthymic, dysthymic with melancholy, and unaffected control groups (Murthy, Gangadhar, Janakiramaiah, & Subbakrishna, 1997, 1998). At 3 months, P300 amplitude increased to control levels in the patient groups after initial values at baseline (7.5 μ V) and 1 month (10.4 μ V) that were well below normal values (14.4 μ V) at both time points. These reports suggest the possibility of some meditation effects on the P300 component.

Visual Stimulus Potentials

Visual EPs. Sensory potentials evoked by a light flashes were used to compare four populations: (a) long-term Qigong meditation practitioners, (b) long-term Nei Yang Gong practitioners (a variant of the older Qigong method), (c) beginning Nei Yang Gong meditators, and (4) nonmeditating controls (W. Zhang, Zheng, Zhang, Yu, &

Shen, 1993). Visual flash potentials were obtained under eyes-open conditions before, during, and after the meditative practice or analogously for a rest period in controls. The flash potentials were classified as early (N80-P115-N150) and late (N150-P200-N280) components, with peak-to-peak amplitudes measured. The long-term traditional Qigong practitioners demonstrated marginally significant decreased amplitude for the early and later flash potentials during meditation. However, the Nei Yang Gong practitioners demonstrated increased amplitudes for both the early and late flash potentials. No effects of meditation were reported for the beginning Nei Yang Gong or control groups. The authors concluded that the two types of Qigong meditative practice produce opposite effects on the relative excitability of the visual cortex, such that the more traditional Qigong leads to cortical inhibition and reduced flash potential amplitudes (Cui & Lui, 1987).

Visual P300. ERPs obtained before and after a 30-min meditation period for experienced yogic meditators or a 30-min rest period for matched nonmeditator controls were compared (Banquet & Lesévre, 1980). A go/no-go task visually presented 450 letters, with 10% randomly omitted. Participants were instructed to respond to each stimulus and to refrain from responding whenever they detected an omitted stimulus, so that state and trait effects could be evaluated under response and nonresponse conditions. For the meditators, P300 amplitude increased postmeditation; for the controls P300 amplitude decreased after rest. The meditators also demonstrated shorter response time (RT) and greater accuracy before and after the meditation period relative to controls; RT was shorter than P300 latency for the meditators but longer than P300 latency for the controls in both the pre- and postconditions. For the meditators compared with controls, P200 amplitudes from both the go and no-go stimuli were larger in the pre- and postmeditation–rest conditions, and N120 amplitude increased in the post-no-go task but decreased in latency in pre- and postconditions for the go task. The authors suggest that long-term meditative practice could increase selective attention capacity, which improves vigilance level to affect ERP measures. Such state effects also are consistent with meditation affecting deautomization of stimulus processing.

Meditative practice and aging in TM meditators were evaluated relative to nonmeditating controls (66 years) with visual ERPs elicited by female and male names in a button-press task (Goddard, 1989, 1992). P300 latency was shorter in meditators than controls (543 vs. 703 ms). The same individuals also performed an auditory oddball task, but neither P300 latency nor RT differed between the groups. The results were interpreted as indicating that trait effects of long-term TM practice are observed only if mental processing demands are increased with more difficult visual tasks. A visual oddball task used to compare four groups of young (20 years) and older (69 years) meditators and controls found that P300 latency and RT increased as the discriminability of the targets was made more difficult for all groups (Goddard, 1992). P300 latencies were longer in older participants in all conditions, whereas RTs were shorter only as task difficulty increased. Further, P300 latencies were shorter in the older meditators versus nonmeditators. These results suggest the possibility of primarily P300 latency trait effects for meditating relative to nonmeditating older individuals.

Somatosensory Potentials

Somatosensory potentials are often evoked using mild electric shocks applied to the median nerve, with a series of potentials

indexing transmission of the signal from the periphery to the cortex (Chiappa, 1996). TM meditators with 2 years practice demonstrated increased amplitudes of early components relative to controls (Petrenko, Orlova, & Liubimov, 1993). Yogic concentrative meditators with a 10- to 12-year practice history evinced amplitude decreases in the later components (Lyubimov, 1999). Similar yogic meditators produced somatosensory EP amplitude decreases when instructed to block out the sensory stimuli, whereas the controls produced no effects. Further, the early components decreased only on the recording sites ipsilateral to stimulation side, but late components decreased bilaterally (Gordeev et al., 1992). This outcome implies that some concentrative meditation practices states can block sensory input at a subcortical level.

CNV

CNV is elicited by presenting two stimuli in succession such that the first serves as an indicator for an impending second stimulus to which a response is required (Walter, Cooper, Aldridge, McCallum, & Winter, 1964). This negative-going waveform was one of the first reported cognitive ERPs and consists of an early deflection related to CNS orienting followed by a later deflection that is maximal before the imperative stimulus and thought to reflect stimulus expectancy (Gaillard, 1977; Irwin, Knott, McAdam, & Rebert, 1966; Rohrbaugh et al., 1997).

An early study found meditation-induced state effects of increased CNV amplitudes following TM practice (Paty et al., 1978). The self-regulation method is a meditation technique combining aspects of Zen practice and autogenic training (Ikemi, 1988; Ikemi, Tomita, Kuroda, Hayashida, & Ikemi, 1986). After a 5-week training course, EEG and CNV assessments were carried out before and during practice as well as during a drowsy state. CNV was obtained with a choice task to the imperative second stimulus. During meditation accuracy increased and shorter RTs were observed, whereas during drowsiness accuracy decreased and longer RTs occurred. EEG demonstrated increased theta and decreased beta power for meditation, but during both meditation and drowsiness reduced CNV amplitudes for the choice-task were found. CNV processes, therefore, may be sensitive to meditation state.

Groups of age-matched TM meditators who differed in length of practice and frequency of self-reported transcendental (defined as experiences of pure consciousness, devoid of thought, and marked by awareness of awareness itself) perceptions (< 1/year, 10–20/year, every day) were evaluated using simple and distracter CNV tasks (Travis et al., 2000). No group effects were observed for the earlier orienting CNV component, but greater negativity for the later expectancy wave was obtained as the frequency of reported transcendental experiences increased across groups and tasks (simple RT, distraction stimuli). The decrement in CNV amplitude induced by the distracting stimuli was inversely related to transcendental experience frequency. The findings implied that transcendental feelings may modulate cortical functioning by activating processing resources to facilitate greater attentional resource capacity and thereby increased CNV amplitude.

A follow-up study assessed groups of older individuals who varied in TM background and reported varied transcendental experience levels: (a) no meditation practice (mean age = 39.7 years), (b) TM practice and occasional transcendental events (mean age = 42.5 years, mean years meditating = 7.8), (c)

long-term TM practice (mean age = 46.5 years, mean years meditating = 24.5) and continuous coexistence of transcendent experience in waking and sleeping states (Travis et al., 2002). For the simple RT task, CNV amplitudes were greater for individuals with more TM practice and greater frequency of transcendent experience. For the choice task, smaller CNV amplitudes were associated with more TM practice and transcendent experience frequency. These findings were interpreted as indicating that the brain of the meditators efficiently waited for the second stimulus information rather than automatically committing attentional resources to the imperative event.

EEG recording during CNV task performance demonstrated increased theta–alpha (6–12 Hz) power across the groups. Frontal broadband coherence values (6–12 Hz, 12–25 Hz, and 25–45 Hz) also were increased as meditation practice increased across groups. These effects suggested that development of transcendental awareness was a meditation trait. Follow-up psychometric assessment of these individuals indicated that greater meditation experience was also related to increased inner directedness, higher moral reasoning, lower anxiety, and more emotional stability (Travis et al., 2004). How self-selection bias of individuals choosing to meditate for long time periods may contribute to these outcomes is unknown.

The CNV findings imply that meditation reduces choice-task CNV amplitude for state (Ikemi, 1988) and trait (Travis et al., 2002). In the simple CNV tasks, an increase in amplitude has been observed as both a state effect and a trait effect of meditation (Paty et al., 1978; Travis et al., 2000, 2002). One finding that may be related to these results is the inverse correlation between states of greater sympathetic activation and CNV amplitude, modifiable by autonomic biofeedback procedures (Nagai, Goldstein, Critchley, & Fenwick, 2004). Thus, CNV appears to be affected by meditative practice in a manner related to changes in attentional resource allocation and possibly autonomic activity.

Conclusions From ERP Meditation Studies

Sensory EP and cognitive ERP meditation assessments have produced a variety of effects. The major difficulties in many studies are a lack of methodological sophistication, no replication of critical conditions, and inconsistency of task and study populations. Some intriguing hints of meditation changing early cortical auditory processing appear reliable, with suggestions that P300 also can be affected by meditation practice. Possible stimulus modality differences in assessing meditation have not been systematically ascertained. Simple CNV tasks yield an increase in amplitude for both state and trait effects of meditation, such that CNV effects may reflect changes in attentional resource allocation.

Brain Imaging and Meditation

Table 3 summarizes the findings from other neuroimaging studies of meditation (reviewed next). The results complement and extend the neuroelectric findings presented previously.

PET

A PET study measured regional cerebral metabolic rate of glucose (rCMRGlc) in yoga meditation by comparing an eyes-

Table 3
Summary of Meditation Studies Using Neuroimaging Methods

Study	Meditation type	N	Experimental design	Method	Findings (state effects)
Herzog et al. (1990)	Yoga meditation, eyes open	8	Meditation vs. resting thought, separate days	PET	Increase: frontal-parietal and frontal-occipital activation ratios, low-resolution analysis Decrease: slight for posterior-anterior ratios
Jevning et al. (1996)	TM	34	Meditators vs. controls, rest → meditation	Rheoencephalography	Increase: frontal, occipital Decrease: none, low-resolution analysis
Lou et al. (1999)	Yoga nidra (guided)	9	Rest → meditation	PET	Increase: anterior parietal (postcentral gyrus), fusiform gyrus, occipital cortex Decrease: dorsolateral orbital, cingulate, temporal, caudate, thalamus, pons, cerebellum
Lazar et al. (2000)	Kundalini yoga mantra	5	Meditation vs. control periods silently generating number lists	fMRI	Increase: DLPFC, ACC, parietal, hippocampus, temporal, striatum, hypothalamus, pre-post central gyri Decrease: 20% globally
Khushu et al. (2000)	Raja yoga	11	Rest → meditation	fMRI	Increase: PFC Decrease: none, low-resolution analysis
Baerentsen (2001)	Mindfulness	5	Rest → meditation	fMRI	Increase: DLPFC, ACC Decrease: occipital
Newberg et al. (2001)	Tibetan Buddhist imagery-meditation	8	Meditators vs. controls, rest → meditation (self-reported peak)	SPECT	Increase: cingulate, inferior-orbital, DLPFC, bilateral thalamus, midbrain, sensorimotor Decrease: PSPL; increases in left DLPFC correlated with decreases in left PSPL
Azari et al. (2001)	Psalm 23 recitation	12	Religious vs. nonreligious participants, rest, reading, and reciting Psalm 23 vs. versus nursery rhyme vs. phone book	PET	Increase: right and left DLPFC, right medial parietal dorsomedial prefrontal (pre-supplemental motor area), cerebellum Decrease: none reported
Kjaer et al. (2002)	Yoga nidra (guided)	5	Separate days for meditation and baseline	PET- ¹¹ C-raclopride binding, EEG	Increase: EEG theta Decrease: raclopride binding in ventral striatum, indicating increase dopamine binding
Ritskes et al. (2003)	Zen	11	Interleaved periods of meditation and rest	fMRI	Increase: DLPFC (R > L), basal ganglia Decrease: right anterior superior occipital gyrus, ACC
Newberg et al. (2003)	Christian prayer	3	Franciscan nuns, rest → prayer	SPECT	Increase: PFC, inferior parietal lobes, inferior frontal lobes Decrease: PSPL
Lazar et al. (2003)	Mindfulness vs. Kundalini yoga	33	Mindfulness vs. Kundalini yoga meditators vs. controls, meditation vs. random number generation	fMRI	Increase: both showed cingulate activation, right temporal lobe (Vipassana only) Decrease: none reported; different distribution of activated networks in the two groups

Note. PET = positron emission tomography; TM = transcendental meditation; fMRI = functional magnetic imaging; DLPFC = dorsolateral prefrontal cortex; ACC = anterior cingulate cortex; PFC = prefrontal cortex; SPECT = single photon emission computed tomography; PSPL = posterior superior parietal lobe; EEG = electroencephalographic; R = right; L = left.

open meditation and a control condition in which the participants were instructed to think of daily affairs (Herzog et al., 1990). The meditators reported feeling relaxed, at peace, and detached during meditation but not during the control condition. Half of the participants showed an overall increase, and half showed an overall

decrease in general cerebral metabolic rate during meditation. This outcome may have resulted from the necessity of recording the two sessions on different days, so that differential practice effects could underlie arousal differences between the groups. No statistically reliable meditation effects on rCMRGlC for any brain regions were

obtained, although mean activation decreases in association with meditation were observed in the superior-parietal (6.30%) and occipital (9.95%) cortices. The rCMRGlc ratios of meditation to control activity yielded three results: (a) The intermediate frontal–occipital ratio increased (from 0.99 to 1.12), (b) intermediate frontal–temporo-occipital activity increased (from 1.18 to 1.25), and (c) superior frontal–superior parietal activation increased (from 1.07 to 1.14). These patterns suggest that the decrease in the occipital area might reflect an inhibition of visual processing during yogic meditation, whereas the relative increase in the frontal cortex could reflect the sustained attention required for meditation. Combined EEG and PET imaging techniques also have demonstrated an association between increased anterior cingulate cortex and dorsolateral prefrontal cortex glucose utilization with frontal midline theta production (Pizzagalli, Oakes, & Davidson, 2003).

A related technique, *rheoencephalography*, quantifies blood flow changes originating from associated variation in electrical impedance. This measure has been shown to index relative cerebral activity reliably, although its resolution is low compared with other methods (Jacquy et al., 1974; Jevning, Fernando, & Wilson, 1989). TM meditators while meditating compared with nonmeditator controls who sat quietly resting demonstrated increased frontal (20%) and occipital (17%) flow rates with no parietal changes observed (Jevning et al., 1996). Because overall arousal level is positively correlated with increased cerebral blood flow (Balkin et al., 2002), these findings are consistent with the subjective reports of increased alertness during TM and bolster the distinction between TM and Stage I–II sleep, because in these states cerebral blood flow is decreased rather than increased (cf. Lazar et al., 2000; Stigsby et al., 1981; Williams & West, 1975).

A PET ($^{15}\text{O-H}_2\text{O}$) study of yoga meditators was conducted while participants listened to a tape recording, with a general instruction followed by distinct and different phases of guided meditative experience (Lou et al., 1999). The control condition consisted of replaying only the instruction phase after meditation conditions, and all sessions were recorded on the same day. A common experience of emotional and volitional detachment was reported throughout the meditation session but not during the control sessions. The meditating individuals practiced intensely for 2 hr before the PET scans and listened to the previously heard tape that presented focusing exercises on body sensation, abstract joy, visual imagery, and symbolic representation of self. Across all meditation phases relative to control conditions, overall increases in bilateral hippocampus, parietal, and occipital sensory and association regions were observed along with general decreases in orbitofrontal, dorsolateral prefrontal, anterior cingulate cortices, temporal and inferior parietal lobes, caudate, thalamus, pons, and cerebellum.

However, each of the guided meditation phases was associated with different regional activations during meditation relative to the control condition: Body sensation correlated with increased parietal and superior frontal activation, including the supplemental motor area; abstract sensation of joy was accompanied by left parietal and superior temporal activation, including Wernicke's area; visual imagery produced strong occipital lobe activation, excluding Area V1; and symbolic representation of self was associated with bilateral activation of parietal lobes. Hence, specific activation was obtained for different meditation conditions, although, given the guided nature, differentiation of these from a

hypnotic state is difficult. Indeed, simultaneous EEG measures demonstrated an 11% increase in theta power in the meditative states over the control condition, which was observed from all 16 electrodes, thereby indicating a generalized increase in theta.

Body sensation meditation and activation of the supplementary motor areas may be due to covert unconscious motor planning, despite participant self-reports of a distinct lack of volitional activity in this study. The meditation on joy and corresponding left-sided activation may have originated from the abstract and verbal nature of the instructions or alternately from the association between left side-dominant frontal activity and positive emotional valence (R. J. Davidson & Irwin, 1999). The visual imagery meditation produced activations similar to voluntary visual imagery, although greater prefrontal and cingulate activity was often observed in the latter. The participants may have had less volitional control and emotional content than might be present in normal visual scene imagining. Similar patterns are observed for REM sleep except that the anterior cingulate is inactivated (Lou et al., 1999). The lack of V1 activation during the visualization meditation adds to a considerable body of evidence suggesting that it is not part of the necessary neural substrate of visual awareness (Koch, 2004). The symbolic representation of the self condition and associated bilateral parietal activity may reflect bodily representation, with temporal cortex activation also implicated (Karnath, Ferber, & Himmelbach, 2001).

The increased hippocampal activity for overall meditation sessions compared with the control state may underlie the increased theta activity, because the increases were not related to prefrontal activation (Kahana, Seelig, & Madsen, 2001). The areas more active in the control state include those that subservise executive attention such as the dorsolateral prefrontal cortex, which has been shown to specifically activate in preparation for voluntary motor activity. Anterior cingulate cortex activation in the control state is thought to be involved in emotional circuits and executive functions. Moreover, the relative control state striatal activation may index low preparedness for action during meditation. Similar regions also have been shown to be decreased in activity during slow-wave sleep, an outcome attributed to the common decreased executive activity in both deep sleep and this form of guided meditation. The cerebellum can participate in attention, motoric feedback loops, as well as prediction of future events (Allen, Buxton, Wong, & Courchesne, 1997), and this structure was less active in the meditative state. In sum, the meditative states produced activity in the hippocampal and posterior sensory–associative systems related to imagery, whereas the control condition was characterized by increased activity for executive–attentional systems and the cerebellum.

A related study of the same meditative state found that dopaminergic changes were associated with the observed decreases in striatal activity, supporting the hypothesis that endogenous dopamine release may increase during the loss of executive control in meditation (Kjaer et al., 2002). Radioactive ^{11}C -raclopride selectively and competitively binds to D2 receptors, such that the amount of binding inversely correlates with endogenous dopamine levels. The findings demonstrated a 7.9% decrease in ^{11}C -raclopride binding in the ventral striatum during meditation, results that correspond to an approximate 65% increase in dopamine release based on rat microdialysis studies of ^{11}C -raclopride binding dynamics in relation to dopamine levels. Increased dopamine

tone underlying the meditative experience may thereby reflect its self-reinforcing nature once proficiency is attained, at least for this form of meditation.

A single photon emission computed tomography (SPECT) study was conducted on Tibetan Buddhist meditators in which participants report “becoming one with” the visualized image (Newberg et al., 2001). The meditators were scanned at baseline and after approximately 1 hr, when they had indicated entering into the deepest part of their meditation session. The baseline activation patterns revealed a difference in the thalamic laterality index in which meditators showed a significantly greater rightward dominance of thalamic regional cerebral blood flow relative to controls. Meditation compared with baseline was related to increased activity in the cingulate gyrus, inferior and orbital frontal cortex, dorsolateral prefrontal cortex, midbrain, and thalamus. The midbrain activation may be correlated with alterations in autonomic activity during meditation (Infante et al., 2001; Kubota et al., 2001; Newberg & Iversen, 2003; Orme-Johnson, 1973; Travis, 2001; Travis & Wallace, 1999; Wenger & Bagchi, 1961). Decreased activity in the left posterior superior parietal lobe was negatively correlated with the activity increase observed in left dorsolateral prefrontal cortex.

Functional MRI (fMRI)

A form of Kundalini yoga entailing a mantra combined with heightened breath awareness was assessed with fMRI (Lazar et al., 2000). The control activity was the mental construction of animal names. Each of the 5 meditation participants, who had practiced Kundalini yoga for at least 4 years, listened to a tape of loud fMRI clicking previous to the scanning sessions to promote meditative focus during this possibly distracting stimulus field. The meditation compared with control conditions produced activity increases in the putamen, midbrain, pregenual anterior cingulate cortex, and the hippocampal–parahippocampal formation, as well as areas within the frontal and parietal cortices. Assessment of early versus late meditation states found robust activity increases in these areas, a greater number of activation foci, larger signal changes, and higher proportion of individuals with significant changes during the late meditation states. These results suggest that, with increased meditation time, individuals produce altered brain states that may index changed states of consciousness as they continue their meditation. Indeed, the major increased activity areas were those subserving attention (frontal and parietal cortex, particularly the dorsolateral prefrontal cortex) and those subserving arousal and autonomic control (limbic regions, midbrain, and pregenual anterior cingulate cortex). The authors specifically point out that their findings were distinct from previous studies as a result of the very different meditation styles (cf. Lou et al., 1999); a guided meditation procedure is particularly susceptible to a lack of executive attentional engagement and, therefore, the lack of prefrontal cortex enhancement.

Individuals with extensive training in Kundalini (mantra-based) or Vipassana (mindfulness-based) meditation were imaged with fMRI during meditation and several control tasks (e.g., simple rest, generation of a random list of numbers, and paced breathing; Lazar et al., 2003). The results indicated that each style of meditation was associated with a different pattern of brain activity. In the two meditator groups, similar but nonoverlapping frontal and parietal

cortices as well as subcortical structures were engaged, and these patterns differed from those observed during control tasks. The main area of common activation was the dorsal cingulate cortex. Vipassana participants experienced little or no decrease in ventilatory rate, whereas Kundalini participants typically had decreases of greater than four breaths/min during meditation compared with baseline. Based on preliminary analyses, different forms of meditation appear to engage different neural structures, as has been previously reported in multiple meditation studies (Dunn et al., 1999; Lehmann et al., 2001; Lou et al., 1999; Lutz et al., 2003).

Zen practitioners were assessed with fMRI using an on–off design of 45-s blocks in which meditators counted their breath as in normal practice during three meditation periods and engaged in random thoughts during the intervening three 45-s rest periods. Comparing meditation with rest revealed increased activity in the dorsolateral prefrontal cortex that was stronger in the right and bilateral basal ganglia. Decreased activity was found in the right anterior superior occipital gyrus and anterior cingulate (Ritskes, Ritskes-Hoitinga, Stodkilde-Jorgensen, Baerentsen, & Hartman, 2003). Activity decrease in the anterior cingulate was not as strong as the increase in dorsolateral prefrontal cortex and was attributed to a decreased experience of will in the meditative state. Given the evidence for anterior cingulate involvement in other studies, this finding may have been related to the very short periods of time allotted for the successive Zen states. A second fMRI study was conducted on 5 mindfulness meditation practitioners; two repetitions of the onset of meditation were assessed as successive 45-s off–on stages of meditation onset (Baerentsen, 2001). Activations in the paired hippocampi, left frontal, right temporal, and anterior cingulate cortices, with deactivations in the visual cortex and left frontal lobe, were observed. These two fMRI studies of Zen techniques found opposite activation patterns for the anterior cingulate. The small sample sizes, lack of phenomenological measures, and their preliminary nature require verification.

The significant increased activations in cingulate cortex and prefrontal and orbitofrontal cortex have been found in the majority of nonguided meditation studies (Herzog et al., 1990; Khushu, Telles, Kumaran, Naveen, & Tripathi, 2000; Lazar et al., 2000, 2003). Besides the importance of anterior cingulate cortex activation as a marker of the increased attentional focus in meditative states, this structure also appears related to feelings of love (Bartels & Zeki, 2000, 2004). Some meditators consistently report such feelings during meditation (Mahesh Yogi, 1963), although these experiences are not the explicit goal in the most commonly practiced meditation techniques such as TM, Vipassana, and Zen (Goleman, 1996; B. A. Wallace, 1999).

The prefrontal areas are activated in attention-focusing tasks not involving the distinct altered sense of relating to experience seen in meditation but are likely related to the effortful intentional activity involved in most meditative practice (cf. Frith, 1991; Pardo, Fox, & Raichle, 1991). Studies comparing internally generated versus externally generated word rehearsal demonstrated a shift from medial prefrontal activation to more lateral areas (Crosson et al., 2001). The increased activity of the dorsolateral prefrontal cortex may contribute to the self-regulation of brain functioning, because it has been shown to contribute to self-regulating emotional reactions (Beauregard, Levesque, & Bourgouin, 2001; Levesque et al., 2003), and decreased emotional reactivity is reported to ensue from meditative practice (Goleman, 2003; B. A. Wallace, 2000).

Engagement of the left superior parietal lobe during visuospatial orientation tasks so that activity decreases in conjunction with the increase in left dorsolateral prefrontal cortex suggests a neural basis for the altered sense of spatial awareness present in the meditative state (cf. Cohen et al., 1996; D'Esposito et al., 1998). Several investigations have reported decreased posterior superior parietal lobe activity associated with decreased experience of self–nonself boundaries (d'Aquili & Newberg, 1993, 1998, 2000), and one found decreased superior parietal lobe activation (Herzog et al., 1990).

A limited number of studies have been carried out with Christian prayer practices. Religious individuals were compared with a nonreligious group during recitation versus reading of Psalm 23, a popular German nursery rhyme, and a telephone book (Azari et al., 2001). The religious individuals reported achieving a religious state while reciting Psalm 23, and significant activations were found in left and right dorsolateral prefrontal cortex, right medial parietal (precuneus), and dorsomedial prefrontal cortex compared with other readings and with nonreligious control individuals. The increases in right dorsolateral prefrontal cortex and dorsomedial prefrontal cortex were especially strong and significantly increased relative to all comparisons. In contrast, the nonreligious individuals reported experiencing a happy state in reciting the nursery rhyme, which was associated with left amygdala activation that was correlated with affective state (LeDoux, 2003; Morris et al., 1996; Phan, Wager, Taylor, & Liberzon, 2004). The authors speculate that a frontoparietal circuit is involved in cognitive processing with felt emotionality, but the lack of a phenomenological religious experience report limits comparisons with previous studies, because meditative training deemphasizes recursive thought.

Franciscan nuns praying were assessed with SPECT in a fashion similar to Tibetan Buddhist meditators (Newberg, Pourdehnad, Alavi, & d'Aquili, 2003). They engaged in centering prayer, which “requires focused attention on a phrase from the Bible” and involves “opening themselves to being in the presence of God” and “loss of the usual sense of space,” making it a relatively good approximation of some forms of mantra-based meditational practices. Compared with baseline, scans during prayer demonstrated increased blood flow in the prefrontal cortex (7.1%), inferior parietal lobes (6.8%), and inferior frontal lobes (9.0%), and a strong inverse correlation between the blood flow changes in the prefrontal cortex and in the ipsilateral superior parietal lobe was found. The findings further suggest that meditative–spiritual experiences are partly mediated through a deafferentiation of the superior parietal lobe, which helps to generate the normal sense of spatial awareness (d'Aquili & Newberg, 2000).

Conclusions and Directions

The current review of meditation state and trait indicates considerable discrepancy among results, a fact most likely related to the lack of standardized designs for assessing meditation effects across studies, the variegated practices assayed, and a lack of technical expertise applied in some of the early studies. EEG meditation studies have produced some consistency, with power increases in theta and alpha bands and overall frequency slowing generally found. Additional findings of increased power coherence and gamma band effects with meditation are starting to emerge. ERP meditation studies are sparse but suggest increased attentional

resources and stimulus processing speed or efficiency. Neuroimaging results are beginning to demonstrate some consistency of localization for meditation practice; frontal and prefrontal areas are shown to be relatively activated. These outcomes appear to index the increased attentional demand of meditative tasks and alterations in self-experience. However, none of the approaches has yet isolated or characterized the neurophysiology that makes explicit how meditation induces altered experience of self. Studies of the reported intense absorptive experience that merges self with the phenomenal world are needed to establish this state effect. Prospective longitudinal assessments are required to establish trait effects that may reflect subtle neural alterations underlying the shift in the locus of self-experience and the development of stable unchanging awareness.

Psychological and Clinical Effects

A number of studies investigating the psychological concomitants to meditation have been conducted and some consistency of results obtained. An important caveat when using subjective reporting of psychological functioning is that the impact of expectancy and performance motivation within meditator participants is difficult to control (Shapiro & Walsh, 1984; West, 1987). Nevertheless, a number of the clinical reports—both psychological and medical—are suggestive of significant effects and, together with the other psychological studies, provide intriguing correlates of the meditation and brain activity findings summarized previously.

The primary psychological domain mediating and affected by meditative practice is attention (R. J. Davidson & Goleman, 1977), but relatively few empirical evaluations of meditation and attention have been conducted. Longitudinal studies of breath-focused meditation in children and adults have reported improved performance on the Embedded Figures Test, which require the individual to ignore distracting stimuli (Kubose, 1976; Linden, 1973). A cross-sectional study of children practicing TM and a cohort of age- and sex-match controls found that meditation practice led to improved measures of attention (Rani & Rao, 1996). Mindfulness and concentrative practices were compared using an auditory counting task susceptible to lapses in sustained attention (Valentine & Sweet, 1995; Wilkins, Shallice, & McCarthy, 1987). Superior attentional performance was obtained for meditators compared with controls as well as long-term compared with short-term meditator status. Further, mindfulness meditators demonstrated better performance than concentrative meditators in a second task assessing sustained attention on unexpected stimuli. In contrast to these trait effects on attentive capacity, short-term meditation effects on a focusing task suggested that TM produced no improvement in concentrative functioning (Sabel, 1980), a finding consistent with the explicit lack of emphasis on concentrative effort using the TM technique.

The CNV studies reviewed previously support the view that attentive capacities are increased in long-term TM meditators relative to controls (Travis et al., 2000, 2002). Given that meditation is a form of attentional training, the neurophysiological findings imply increased activity in the frontal attentional system; additional studies are needed to confirm this hypothesis. A related clinical study assessed the impact of a yogic concentrative meditative practice on attention-deficit/hyperactivity disorder in adolescents; findings indicate a substantial improvement in symptoms

after a 6-week training intervention (Harrison, Manoch, & Rubia, 2004).

The psychological trait *absorption* is related to attentional deployment and appears to have relevance to meditative practice (Tellegen & Atkinson, 1974). Absorption refers to the tendency to have episodes of total attention that occupy representational resource mechanisms, thereby leading to transient states of altered self and reality perception. The data suggest that absorption and anxiety reduction are independently related to proficiency in meditative practice, but it is not clear whether this is due to a predisposition for meditative practice or a result of such practice (R. J. Davidson, Goleman, & Schwartz, 1976). Further research assessing the neurophysiological functioning of meditators with regard to absorption might be of benefit in characterizing the individual differences for the range of brain and mind responses to meditative training (Ott, 2003).

Perceptual sensitivity is a psychological domain that appears to be impacted by meditation (Goleman, 1996). The ERP studies reviewed previously are consonant with the general view that meditation may lead to improvements in perceptual acuity or processing, but rigorous tests of perception effects are scarce. A study on perceptually ambiguous visual stimuli with a binocular rivalry task demonstrated that one-pointed concentrative meditation may stabilize one of the perceptual possibilities in awareness (Carter et al., 2005). More germane to reports of enhanced perceptual clarity, visual sensitivity threshold to short light flashes was lower in mindfulness meditators than controls, and a 3-month intensive mindfulness meditation retreat seemed to produce further decreases in threshold (D. P. Brown et al., 1984a, 1984b). Studies of yogic concentrative meditation (Sahaj yoga) have found that children, young adults, and adults evince improvements in critical flicker-fusion frequency after training compared with control groups who did not undergo such training (Manjunath & Telles, 1999; Raghuraj & Telles, 2002; Telles, Nagarathna, & Nagendra, 1995). Visual contrast sensitivity was also shown to increase secondary to Sahaj yoga training in a group of epileptic adults (Panjwani et al., 2000). The long-standing descriptions of the enhancement of the perceptual field resulting from meditation combined with the suggestive effects reviewed here and the consistency with event-related potential findings warrant further studies of perceptual acuity, preferably in combination with neurophysiological monitoring.

A considerable body of research supports the idea that meditative training can mitigate the effects of anxiety and stress on psychological and physiological functioning. The functional plasticity of the CNS affords significant neurophysiological state changes that may evolve into trait effects secondary to the long hours of practice, stylized attentional deployment, reframing of cognitive context, and emotional regulation involved in meditative training (R. J. Davidson, 2000). This possibility is consonant with the relationships among increased stress, increased corticosteroid levels, and inhibition of hippocampal neurogenesis (McEwen, 1999). Meditation decreases experienced stress load (Carlson, Speca, Patel, & Goodey, 2003; R. J. Davidson et al., 1976; Eppley, Abrams, & Shear, 1989; Gaylord et al., 1989; Holmes, 1984; Kabat-Zinn et al., 1992; Lehrer et al., 1980), which appears related to decreased cortisol and catecholamine levels (Carlson, Speca, Patel, & Goodey, 2004; Infante et al., 1998, 2001; Kamei et al., 2000; MacLean et al., 1994, 1997; Michaels, Parra, McCann, &

Vander, 1979; Sudsuang, Chentanez, & Veluvan, 1991). Some studies with meditators have assessed physiological responses to stressful stimuli, which is particularly relevant given the purported benefits of decreased automatization and reactivity combined with greater calm and compassion resulting from meditation (Kabat-Zinn, 1990; Goleman, 2003; Mahesh Yogi, 1963). Meditators exhibited a quicker return to baseline for heart rate and skin conductance measures after exposure to stressful film clips (Goleman & Schwartz, 1976). Meditators also were shown to lack frontal gamma induction found for nonmeditators in response to stressful film clips (Aftanas & Golosheikine, 2005). These studies are preliminary but provide motivation to further study neurophysiological response to emotionally challenging stimuli.

Mindfulness-based practices have produced positive clinical outcomes for anxiety, immunoprotective functioning assays, pain, and stress-related skin disorders (Beauchamp-Turner & Levinson, 1992; Carlson et al., 2003, 2004; R. J. Davidson et al., 2003; Kabat-Zinn, 1982, 2003; Kabat-Zinn, Lipworth, & Burney, 1985; Kabat-Zinn et al., 1998; J. J. Miller, Fletcher, & Kabat-Zinn, 1995; Shapiro & Walsh, 2003). These results are consistent with the hypothesis that meditation induces a significant reorganization of frontal hemispheric activity associated with emotional reactivity and outlook perhaps related to the increases in theta and alpha EEG activation (R. J. Davidson, 2000; R. J. Davidson et al., 2003). Concentrative practices also have been examined in medical contexts (Castillo-Richmond et al., 2000; Murthy et al., 1998; Schneider et al., 1995; Zamarra, Schneider, Besseghini, Robinson, & Salerno, 1996); low-effort mantra-based TM is the most frequently evaluated complementary therapy contributing to decreasing the impact of stress (Gelderloos, Walton, Orme-Johnson, & Alexander, 1991; Jevning et al., 1992; Walton, Pugh, Gelderloos, & Macrae, 1995). In this context, it would be helpful to obtain concurrent neurophysiological measures with the assessment of medical or psychological outcome to characterize the neural mediating factors associated with clinical improvement. Examples of this approach include observed left-over-right asymmetry shifts of frontal activity that correlated with increases in immune measures secondary to mindfulness meditation training (R. J. Davidson et al., 2003) as well as increases in auditory P300 amplitude correlated with improvements in depression in response to yogic meditation (Murthy et al., 1997, 1998). Further research into meditation and the biological mechanisms of stress and emotional reactivity would provide needed substantiation for theories implicating such practice in the functional reorganization of stress-related limbic structures (Esch, Guarna, Bianchi, Zhu, & Stefano, 2004).

Meditative practices using mental role-playing and the generation of specific sustained feelings or intentions of love and compassion have begun to be investigated (Goleman, 2003; Lehmann et al., 2001; Lutz et al., 2004). However, meditation effects on emotional functioning have not been extensively explored with neuroimaging methods, even though clinical studies suggest that the psychological variable mindfulness is enhanced through meditative practice and seems to be a powerful mitigator of susceptibility to depression. In particular, mindfulness-based cognitive therapy, which commonly incorporates mindfulness meditation, has been successful in treating depression (Ma & Teasdale, 2004; Mason & Hargreaves, 2001; Rohan, 2003; Segal, Williams, & Teasdale, 2002; Teasdale, Segal, & Williams, 1995; Teasdale et

al., 2000). The specific effects appear related to the prevention of depression relapse in patients already experiencing three or more previous depressive episodes (Teasdale et al., 2000).

The psychological variable most associated with the increased resistance to depression after mindfulness-based cognitive therapy is metacognitive awareness, the shift toward experiencing negative thoughts as observable mental contents rather than the self (Teasdale et al., 2002). As with stress, depression is linked to increased cortisol and decreased hippocampal neurogenesis (E. S. Brown, Rush, & McEwen, 1999; Gould, Tanapat, Rydel, & Hastings, 2000; B. L. Jacobs, 2002; Malberg & Duman, 2003; Thomas & Peterson, 2003; Vollmayr, Simonis, Weber, Gass, & Henn, 2003), implicating meditative training in eliciting a cascade of neuroprotective events that are possibly related to the enhancement of the frontal attentional control system or the decreased arousal associated with alpha increases. The increase in metacognitive awareness that seems associated with the efficacy of mindfulness-based approaches to therapy is difficult to reconcile with current neuroimaging data but appears related to the fundamental goals of meditative practice in producing lasting impact on the self–nonself relationship (Austin, 2000; Levenson, Jennings, Aldwin, & Shiraishi, 2005; Walsh, 1982). The development of a number of experimental paradigms aiming to assess the subtleties of self-referential processing in health and illness provides a means to quantify further psychometrically derived claims for changes in self-experience with brain-based measures (Kircher & David, 2003; Kircher et al., 2000; Lou et al., 2004; Platek, Keenan, Gallup, & Mohamed, 2004).

Understanding the state and trait neurophysiological and psychological changes induced through meditative practices requires better psychometric assessment of the elicited states and traits. Several investigators have produced such measures for both state and trait changes (K. W. Brown & Ryan, 2003; Buchheld, Grossman, & Walach, 2001; Levenson et al., 2005; Ott, 2001; Piron, 2001). Such trait-based research suggests that the psychological variable mindfulness, which has influenced theories of psychological intervention, is increased after meditative training and associated with the experience of well-being (K. W. Brown & Ryan, 2003). A proposal to pare down altered states of consciousness into a four-dimensional state space consisting of activation, awareness span, self-awareness, and sensory dynamic constructs is an appealing proposal for meditation research as well (Vaitl et al., 2005). This approach provides encompassing signatures of experienced state that may map more easily than higher dimensional state spaces onto neurophysiological differences, although this limited four-dimensional space may not adequately address the full range of alterations induced by meditation (Travis et al., 2004; Walsh, 1982; Wilber, Engler, & Brown, 1986).

Given the wide range of possible meditation methods and resulting states, it seems likely that different practices will produce different psychological effects and that different psychological types will respond with different psychobiological alterations. Indeed, reports have shown that novices in Zen meditation demonstrated low trait anxiety correlated with frontal alpha coherence effects (Murata et al., 2004), whereas novelty seeking scores correlated with frontal alpha power increases and harm avoidance scores correlated with frontal theta increases (Takahashi et al., 2005). These findings are preliminary in nature but serve as a potentially important model for how psychological set may be

related to meditation state neurophysiology. Quantification of the trait changes elicited by given different mental sets may foster insight into specific avenues of meditation's psychobiological impact; rigorous comparison of techniques is needed to identify specific psychological outcomes.

Additional Future Directions

As outlined previously, several studies have suggested that different meditation practices lead to different neurophysiological outcomes, so that the neurophenomenological comparison of meditative practices with other methods of altered state induction are becoming warranted to isolate the functional brain activity associated with psychological states. Assessments of psychological changes, clinical outcomes, and state–trait neuroactivity markers across meditative practices will be necessary for developing the clinical utility of these methods. Targeted assays of theta, alpha, and gamma power as well as coherence effects in both state and trait studies of meditation will help establish a necessary database for future applications.

A major challenge for basic meditation research is the clear quantitative differentiation and topographic mapping of the difference between meditation and early sleep stages. The most widely found state effects of meditation—periods of alpha and theta enhancement—overlap significantly with early drowsing and sleep states (Corby et al., 1978; Pagano et al., 1976; Rechtschaffen & Kales, 1968; Younger et al., 1975). The increases in theta power observed in some long-term meditators may be related to learning to hold awareness at a level of physiological processing similar, but not identical, to sleep Stage I. Awareness maintenance practice may enhance awareness even as deep sleep develops, thereby affecting associated neurophysiological markers.

This hypothesis provides a phenomenological link between the physiological similarities of the meditative- and sleep-related states. In both cases, there is an increased access to a witnessing awareness of state. It may be that the difference between the slow activity in meditative practices and that of normal sleep reflects the distribution of theta versus alpha power changes, the increases in theta and alpha coherence during meditation versus decreases during sleep, and possibly the high-frequency activity that accompanies increases in low-frequency power with meditation practice that are decreased in sleep. The theta increase in meditative states is the frontal midline theta generated by the anterior cingulate, dorsal, and medial prefrontal cortices (Aftanas & Golocheikine, 2001; Asada et al., 1999; Hebert & Lehmann, 1977; Ishii et al., 1999). The theta typically seen at the transition from Stage I to Stage II sleep is less stable across time and also originates from more widespread sources. A comprehensive empirical distinction of these two increased theta states could provide a much-needed differentiation between the phenomenology of meditative experience and that of sleep.

Conclusion

Meditation states and traits are being explored with neuroelectric and other neuroimaging methods. The findings are becoming more cohesive and directed, even though a comprehensive empirical and theoretical foundation is still emerging. CNS function is clearly affected by meditation, but the specific neural changes and

differences among practices are far from clear. The likelihood for clinical utility of meditation practice in conjunction with psychological and neuropharmacological therapies is a strong impetus for future studies. The present review has attempted to set the stage for this development by providing an organized state-of-the-art summary of how meditation affects the brain.

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