Improving Executive Function and Its Neurobiological Mechanisms Through a Mindfulness-Based Intervention: Advances Within the Field of Developmental Neuroscience

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ABSTRACT—***Poor executive function (EF) has been associated with a host of short- and long-term problems across the lifespan, including elevated rates of attention deficit hyperactivity disorder, depression, drug abuse, and antisocial behavior. Mindfulness-based interventions that focus on increasing awareness of one's thoughts, emotions, and actions have been shown to improve specific aspects of EF, including attention, cognitive control, and emotion regulation. Reflecting a developmental neuroscience perspective, this article reviews research relevant to one specific mindfulness-based intervention, integrative body-mind training (IBMT). Randomized controlled trials of IBMT indicate improvements in specific EF components, and uniquely highlight the role of neural circuitry specific to the anterior cingulate cortex and the autonomic nervous system as two brain-based mechanisms that underlie IBMT-related improvements. The relevance of improving specific dimensions of EF through short-term IBMT to prevent a cascade of risk behaviors for children and adolescents is described and future research directions are proposed.***

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Executive function (EF) is a central component related to an individual's capacity to adaptively regulate his or her thoughts, emotions, instincts, and actions (Posner & Rothbart, 2009). EF involves delay of reward, planning, implementation of coherent goals, and many other processes. Key to each of these EF processes is the ability to resolve conflict between competing emotions or response tendencies (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Rothbart, 2011). EF thus comprises a broad category of discrete but interrelated cognitive processes, including attentional control, attention shifting, cognitive flexibility, self-monitoring, planning, inhibitory control of prepotent responses, and working memory. In this article, we describe a mindfulness-based intervention focused on improving several specific components of EF (attentional control, self-regulation, ability to resolve conflicting information), behavioral correlates of these EF components (improved positive mood and reduced negative mood), and two neurobiological mechanisms that have been associated with these EF skills, the anterior cingulate cortex (ACC) and the autonomic nervous system (ANS).

EXECUTIVE FUNCTION AND DEVELOPMENT

Extant studies indicate robust associations between deficits in components of EF (i.e., self-regulation problems, attentional control difficulties) and a host of negative outcomes across the lifespan, including behavior problems, aggression, antisocial behavior, inattention, attention deficit hyperactivity disorder (ADHD), problems with peers, school failure, depression, and substance abuse during childhood and adolescence (Eigsti et al., 2006; Floyd & Kirby, 2001; Ivanov, Schulz, London, & Newcorn, 2008; Mahone & Hoffman, 2007; Moffitt et al., 2011; Perner, Kain, & Barchfeld, 2002; Riggs, Blair, & Greenberg, 2003). Conversely, higher levels of these EF components have been associated with positive developmental outcomes, including improved "on-task" behavior, better perspective-taking skills, and greater self-efficacy, mastery, self-esteem, professional attainment, and relationship success, as well as positive social, emotional, behavioral, economic, and physical health outcomes (Blair & Peters, 2003; Carlson, Mandell, & Williams, 2004; Carlson & Moses, 2001; Moffitt et al., 2011). Regulation and expression of emotionality appear to be critical underpinnings of adaptive EF development (Eisenberg et al., 1997; Garstein & Rothbart, 2003), and both EF and emotion-regulation skills show age-related changes across early childhood (Best, Miller, & Jones, 2009; Lipscomb et al., 2011).

These findings have promoted the development of intervention strategies aimed at improving EF proficiency early in development in order to promote more positive developmental outcomes later in life (Duckworth, 2011). In particular, there has been a surge in the development of mindfulness-based interventions targeting improved developmental outcomes in children and adolescents (see Greenberg & Harris, 2011, for a review). Below we describe one such intervention, integrative body-mind training (IBMT), and summarize evidence for its efficacy. Identifying mechanisms and interventions that promote the development of specific EF skills early in life may have substantial implications for the development of well-being across the life course.

MINDFULNESS-BASED INTERVENTIONS TARGETING EF AND ASSOCIATED BEHAVIORS

Mindfulness-based interventions (MBIs) are composed of several key components aimed at progressively orienting the participant to an awareness of the connection and synergy between body and mind. Techniques employed to attain this state include body relaxation, breathing practice, mental imagery, and body and mind awareness (Chiesa & Malinowski, 2011; Kabat-Zinn, 1990; Lutz, Slagter, Dunne, & Davidson, 2008; Tang, 2009; Tang & Posner, 2009; Tang et al., 2007; Tang et al., 2009). MBIs vary in their methods, quality, and dosage, and some have been shown to improve attention, emotion regulation, and social relationships in children and adults (Black, Milam, & Sussman, 2009; Bowen et al., 2006; Chiesa & Malinowski, 2011; Chiesa & Serretti, 2010; Greenberg & Harris, 2011; Lutz et al., 2008; Tang & Posner, 2009; Tang et al., 2007; Zylowska et al., 2008). However, as noted in a recent review (Greenberg & Harris, 2011), the majority of research with children and adolescents in this area has lacked scientific rigor. For example, a review by Birdee et al. (2009) identified 19 mindfulness-based interventions for children (yoga based) and concluded that most did not adequately quantify key design elements, such as instructor qualifications, attrition, and randomization methods, and/or most used inappropriate data analytic techniques. Below we summarize the scientific evidence for IBMT—one example of an MBI—across the lifespan. IBMT has been tested in several randomized clinical trials (RCTs) using relaxation training as a control (Tang, 2005, 2007, 2009; Tang et al., 2007; Tang et al., 2009; Tang et al., 2010). We begin by providing a brief description of the IBMT intervention; additional details of the intervention are available in Tang and colleagues (Tang et al., 2007; Tang et al., 2009; Tang et al., 2010).

THE IBMT INTERVENTION

IBMT Core Components

The IBMT intervention involves body relaxation (e.g., conscious relaxation of muscle sets), mental imagery (e.g., imaging a calm sea), and mindfulness training (e.g., awareness of one's thoughts without judging them). The IBMT method stresses making no effort, or less effort, to control one's thoughts and promotes a state of restful alertness that allows a high degree of awareness of one's body, breathing, mind, and of external instructions. The goal of IBMT is to achieve a meditative state through the development of a strong mind–body connection; for example, relaxing the body and becoming increasingly aware of the relaxation feelings and the resulting sensations are two strategies that facilitate entry into the meditative state. The combined use of body and mind training is supported by studies of embodied cognition, in which changes in the body, particularly in facial expression, influence emotional processing, facilitate retrieval of autobiographical memories, and enhance feelings of personal self-efficacy and control (Dijkstra, Kaschak, & Zwaan, 2007; Huang, Galinsky, Gruenfeld, & Guillory, 2011; Niedenthal, 2007). A qualified IBMT coach guides participants in their training by providing supporting instructions throughout the practice sessions. A qualified coach is someone who has completed IBMT training and passed associated certification tests, participated actively in the IBMT intervention as part of training, and demonstrated the ability to effectively interact with the trainees. The role and skill of the coach in effectively engaging intervention participants (i.e., using a developmentally appropriate approach to help participants enter a meditation state) is critical, especially when working with adolescents and children (Tang, 2005, 2007, 2009).

IBMT Procedures

IBMT practice is typically conducted in a group setting. It includes (a) a presession (approximately 5 min), (b) a practice session (approximately 20 min), and (c) a postsession (approximately 5 min). In the presession, the IBMT coach reviews the instructions for the practice session, interacts with the participants, and helps guide them into a quietness and mindfulness state. In the practice session, the participants follow IBMT instructions on a compact disk that includes background music to help the participants enter a meditative state. During the practice session, the IBMT coach observes facial and body cues to identify participants who are struggling with the method and provides feedback to them either immediately or after the session. The practice sessions are intended to help each participant increase the length of time spent in the meditation experience; thus, the quality of meditation generally improves with each session. In the postsession, the IBMT coach facilitates a brief group discussion to help ensure that participants have positive experiences consonant with the intent of IBMT (Tang, 2007, 2011; Tang et al., 2007; Tang et al., 2009).

Although the general IBMT procedures are similar for all age groups, several modifications are made based on the age and/or ability of participants. For example, the IBMT coach often instructs older adults to practice each technique slowly and comfortably, consistent with their regular pace of physical and metal activity. With adolescents, who are in an important transitional stage of emotional, behavioral, cognitive, and physical development that may be particularly responsive to mindfulness training, the coach modifies the training by describing the scientific research pertaining to it and explains its working mechanisms to help motivate participants to follow the training. With children in the preschool period, which has shown to be a critical time for the development of self-control, with long-term effects for children who show deficits in this area (e.g., Moffitt et al., 2011), IBMT modification includes the coach's use of cartoons or stories to create an environment that helps the children enter the meditative state (Tang, 2007). In sum, the qualified coach plays a key role in assisting participants in different age groups to enter and maintain the meditation state (Tang, 2009; Tang et al., 2007).

SPECIFIC EF COMPONENT AND BEHAVIORAL OUTCOMES ASSOCIATED WITH IBMT

As noted above, several RCTs have been conducted to test the efficacy of IBMT. Below, we briefly review results of three studies with different age groups that compared the effects of 5–30 days of IBMT with those of relaxation training over the same schedule.

In Study 1, Chinese undergraduates were randomly assigned to either an experimental group (IBMT, $n = 40$) or to an active control group ($n = 40$) using a prestudy–poststudy design (Tang et al., 2007). The experimental group was given group training 20 min per day for 5 days; the control group was given the same amount of relaxation training. Relaxation training was guided by a tutor and a compact disk with music and instruction and involved relaxing different muscle groups (e.g., face, head, shoulders, arms, legs, chest, back, abdomen, etc.). Analyses indicated that after 5 days of training, the IBMT group showed significantly greater improvement in executive attention during the Attention Network Test (Fan, McCandliss, Sommer, Raz, & Posner, 2002) than did the control group. In addition, individuals in the IBMT condition had lower negative affect and fatigue, and higher positive feelings on the Profile of Mood States (Shacham, 1983).

In Study 2, 489 Chinese middle school and high school students were given 6 weeks of 30-min IBMT training per day prior to their local and national high school and college entry examinations. Compared to a randomized active control group, the IBMT group showed greater improvement in attention (sustained attention and selective attention tasks), positive emotion, Raven test scores, and academic performance (scores of literacy, math, and second language), as well as in social behavior (Tang, 2005, 2009).

Study 3 (Yang, Song, Shen, Cui, & Tang, 2010) tested the efficacy of IBMT with 60 Chinese children aged 4–5 years, using cartoons and stories to create an environment that would help the children enter the meditative state. Results of this randomized controlled trial were consistent with the IBMT studies with adolescents and adults: Ten hr of IBMT significantly increased children's self-control scores on the Child Behavior Questionnaire (Rothbart, Ahadi, Hershey & Fisher, 2001) and improved their EF on two observed tasks in comparison to an active control condition that included a classroom activity (Diamond & Lee, 2011). Overall, this programmatic set of three studies suggests that IBMT is effective across the lifespan in improving the specific components of EF.

NEUROBIOLOGICAL MECHANISMS UNDERLYING IBMT

What are the mechanisms by which IBMT produces changes in specific EF components, including attention and self-regulation? As described above, IBMT is intended to modify brain states by increasing the brain–body connection of participants during the meditation sessions. Brain states refer to reliable patterns of brain activity that involve the activation or connectivity of multiple large-scale brain networks that are identifiable even when not engaged in a specific task (Bressler & Menon, 2010). Brain-state changes refer to the shift between certain forms of experience, such as sleepiness and wakefulness, or meditation and exercise. These experiences share an altered state of mind and body. IBMT is hypothesized to improve attention and self-regulation through brain state changes involving both body and mind.

Two indicators of brain-state changes are increased activity in the prefrontal cortex and changes in heart rate variability. Specifically, neuroimaging studies have indicated that discrete interrelated aspects of EF, including attentional control, attention shifting, cognitive flexibility, self-monitoring, planning, inhibitory control of prepotent responses, and working memory, are associated with activation of the prefrontal cortex (Roth, Randolph, Koven, & Isquith, 2006; Wood & Smith, 2008). In particular, the ACC is a key brain region in the prefrontal cortex that has been associated with EF (see reviews by Bush, Luu, & Posner, 2000; Posner, Rothbart, Sheese, & Tang, 2007). Tang and colleagues therefore hypothesized that IBMT would show corresponding changes in the prefrontal cortex (the ACC in particular), illustrating a neurobiological mechanism underlying the behavioral improvements in EF reviewed above (Tang et al., 2009). Since changes in heart rate variability reflect activation of the ANS, they also hypothesized that IBMT would show effects on heart rate variability. Below we summarize evidence from two studies (referred to here as Studies 4 and 5) suggesting that these two neurobiological systems are activated by IBMT.

In Study 4, Tang and colleagues randomly assigned 46 Chinese undergraduates to IBMT or relaxation groups and conducted brain-imaging assessments before, during, and after 5 days of IBMT and relaxation training (Tang et al., 2009). Neuroimaging data demonstrated that individuals in the IBMT condition showed stronger subgenual and adjacent ventral ACC activity compared to individuals in the control condition. In Study 5, a new sample of 40 Chinese undergraduates was randomly assigned to IBMT or relaxation groups, and EEG data and physiology data were collected before, during, and after 5 days of IBMT and relaxation training (Tang et al., 2009). The results of this study indicated that frontal midline ACC theta correlated with high-frequency heart rate variability among individuals in the IBMT condition, suggesting control by the ACC over parasympathetic activity. Together, these studies indicate that both the ACC and ANS may serve as mediating brain mechanisms linking IBMT with improvements in EF.

Additionally, Tang and colleagues collected physiological measures, including heart rate, skin conductance response, and respiratory rate and amplitude from Study 4 and Study 5 participants to monitor ANS activity (Tang et al., 2009). After 5 days of training, individuals in the IBMT group in both studies showed better ANS regulation by a ventral midfrontal brain system than did the relaxation group. The researchers propose that this changed brain state may be a result of training in the coordination and balance of body and mind given in the IBMT. In addition, during and after training, the IBMT group across both studies showed significantly better physiological reactions in heart rate, respiratory amplitude and rate, and skin conductance response than did the relaxation control group. Differences in heart rate variability and skin conductance response suggested greater involvement of ANS in the IBMT group during and after training.

Similar results were found in Study 3, in which 20 of the 60 Chinese preschoolers originally participating in this study (n = 10/group) received parental consent to participate in a second study component that examined event-related potential (ERP) using a go/no-go task. Results indicated that the IBMT intervention significantly changed the amplitude of the ERP component P3 thought to involve the ACC (Ilan & Polich, 1999). Children in the control condition did not show such effects, suggesting that the IBMT intervention produced inhibitory control improvements associated with better executive function and self-regulation (Yang et al., 2010).

Dosage Effects

As noted in recent reviews (e.g., Greenberg & Harris, 2011), many existing mindfulness-based interventions fail to consider dosage effects. To address this issue, Tang and colleagues conducted a sixth study that comprised 4 weeks of training (11 hr total) using a randomized controlled trial design to compare IBMT with a relaxation training control condition. As described above, Studies 1 through 5 indicated that with less than 3 hr of total training in IBMT, individuals saw improvements in attention and self-control, increases in positive emotion, and reductions in stress. They also experienced improved cortisol reactivity and improved immune function through a central (brain) and autonomic (body) nervous system function (Tang et al., 2007; Tang et al., 2009). Study 6 addressed the question of whether there are additional potential benefits of IBMT practice when implemented over a longer period of time. In Study 6, compared to relaxation training, 4 weeks of IBMT significantly improved the basal immune function (Fan, Tang, Ma, & Posner, 2010) and the efficiency of alerting and executive attention networks (Tang, 2009). In contrast, the 1-week IBMT improved only the executive attention network (Tang et al., 2007).

On the basis of this evidence, Tang and colleagues conducted a seventh study to test the hypothesis that 11 hr of training with IBMT over 4 weeks would increase fractional anisotropy, which is an index representing the integrity and efficiency of white matter in the corona radiata, an important white-matter tract connecting the ACC to other structures (Tang et al., 2010). In this study, the researchers randomly assigned 45 U.S. undergraduates to an IBMT or relaxation group and acquired brain images from each participant at rest using MRI diffusion tensor imaging for analysis of white matter before and after training. Results showed that 11 hr of IBMT increased fractional anisotropy connecting ACC to other regions. Because deficits in activation of the ACC have been associated with many disorders, including mood disorders and substance abuse, the ability to strengthen cingulate connectivity through training could provide a means for improving EF and might serve as a possible therapy or prevention tool (Tang et al., 2010).

SUMMARY AND FUTURE DIRECTIONS

Deficiencies in EF are associated with a host of problems across the lifespan, such as mood disorders, school failure, substance abuse, and antisocial behavior. The series of RCT studies of IBMT described in this article indicate the positive effects of IBMT on several components of EF, including attentional control, emotion regulation, and response to stress (Tang, 2005, 2007, 2009, 2011; Tang & Posner, 2009; Tang et al., 2007; Tang et al., 2009; Tang et al., 2010). In addition, this work highlights the ACC and the ANS as neurobiological mechanisms underlying the behavioral changes seen in specific EF components through IBMT. Recent studies also indicate the important role of the ACC in MBIs (for a review, see Hölzel et al., 2011). An advantage of IBMT is that it has been tested with randomized trials that have included an active control condition consisting of relaxation training, which is often used to improve performance. Consequently, the effects of the IBMT intervention cannot be due simply to contact with a trained interventionist but, rather, are specific to the components of the IBMT intervention. As reviewed above, changes induced by IBMT can occur after as little as 5 days of training, but are greater with longer training periods. However, it is unknown the extent to which the effects of IBMT persist a year or more after training. This research has implications for the prevention of risky behaviors such as drug use; for example, if IBMT or other effective MBIs can be used with at-risk populations of children, improvement in specific components of EF, including self-regulation and attentional control, might then prevent the development of subsequent problems such as school failure and substance use.

The improvements reflected in the IBMT studies conducted to date have included normative or community-based samples rather than samples indicated for clinical problems such as ADHD. We believe that the theory underlying IBMT would suggest similar improvements in EF are possible in clinical populations, but work in this important area has yet to be conducted. We do not know which features of IBMT are of greatest importance in obtaining change. We believe that the integration of the various mindfulness components into one single training package may explain why IBMT is effective at such a low dose, but the components have yet to be tested individually. The role of the IBMT trainer could also be a central effective ingredient, and thus requires additional research (Posner, Rothbart, Rueda, & Tang, 2010; Tang, 2009; Tang et al., 2007; Tang et al., 2010).

In summary, IBMT is one of many MBIs. Although its benefits have been verified using random assignment trials that have included a relaxation control condition, additional research and intervention development are needed with not only IBMT but also with other promising MBIs, given the preliminary evidence for such interventions to improve EF and associated behavioral outcomes.

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