Appl Psychophysiol Biofeedback
DOI 10.1007/s10484-010-9134-x

Emotion Self-Regulation, Psychophysiological Coherence, and Test Anxiety: Results from an Experiment Using Electrophysiological Measures

**Raymond Trevor Bradley · Rollin McCraty ·
Mike Atkinson · Dana Tomasino · Alane Daugherty ·
Lourdes Arguelles**

Abstract This study investigated the effects of a novel, classroom-based emotion self-regulation program (TestEdge) on measures of test anxiety, socioemotional function, test performance, and heart rate variability (HRV) in high school students. The program teaches students how to self-generate a specific psychophysiological state—*psychophysiological coherence*—which has been shown to improve nervous system function, emotional stability, and cognitive performance. Implemented as part of a larger study investigating the population of tenth grade students in two California high schools ($N = 980$), the research reported here was conducted as a controlled pre- and post-intervention laboratory experiment, using electrophysiological measures, on a random stratified sample of students from the intervention and control schools ($N = 136$). The Stroop color-word conflict test was used as the experiment's stimulus to simulate the stress of taking a high-stakes test, while continuous HRV recordings were gathered. The post-intervention electrophysiological results showed a pattern of improvement across all HRV measures, indicating that students who received the intervention program had learned how to better manage their emotions and to self-activate the psychophysiological coherence state under stressful conditions. Moreover, students with high test anxiety exhibited increased HRV and heart rhythm coherence even during a resting baseline condition (without conscious use of the program's techniques), suggesting that they had internalized the benefits of the intervention. Consistent with these results, students exhibited reduced test anxiety and reduced negative affect after the intervention. Finally, there is suggestive evidence from a matched-pairs analysis that reduced test anxiety and increased psychophysiological coherence appear to be directly associated with improved test performance—a finding consistent with evidence from the larger study.

Keywords Test anxiety · Emotion self-regulation · Student stress · Heart rate variability/HRV · Coherence · Psychophysiology · Biofeedback

Introduction

The increased emphasis on standardized testing in the U.S. educational system has led to a growing concern about the

---

R. T. Bradley · D. Tomasino
Institute for Whole Social Science, Aorangi Retreat, Hikurangi
RD 1, Northland, New Zealand
e-mail: wholesocialscience@gmail.com;
ray.bradley@neurondynamics.com

D. Tomasino
e-mail: dana.tomasino@gmail.com

R. T. Bradley
Center for Advanced Research, Neuron Dynamics, Appleton, WI
54915, USA

R. McCraty (✉) · M. Atkinson
HeartMath Research Center, Institute of HeartMath, 14700 West
Park Avenue, Boulder Creek, CA 95006, USA
e-mail: rollin@heartmath.org

M. Atkinson
e-mail: mike@heartmath.org

A. Daugherty
Department of Health Science, California State University
Polytechnic, Pomona, CA 91768, USA
e-mail: adaugherty@csupomona.edu

L. Arguelles
School of Educational Studies, Claremont Graduate University,
Claremont, CA 91711, USA
e-mail: Idyllcuban@aol.com

test-related anxiety experienced by many students (Cizek and Burg 2006; Erford and Moore-Thomas 2004; Hartnett-Edwards 2008; Sears and Milburn 1990). It has long been known that students with moderate to high levels of test anxiety have depressed test performance (Hembree 1988; Hill 1984; Wigfield and Eccles 1989). The estimates from previous studies of the percentage of students who suffer from test anxiety vary widely, ranging up to 40% (see Cizek and Burg 2006; Zeidner 1998). The larger study, from which the experiment reported in this article is drawn, recently found that while many (61%) high school students reported suffering from test anxiety at least some of the time, as many as one-quarter (26%) were afflicted "almost always." Moreover, test anxiety was found to have a significant negative impact on student performance on standardized tests (Bradley et al. 2007). These are sobering statistics. The enormous challenge facing educators is how best to prepare students for testing so that their performance is reflective of their true academic ability, thus providing students, parents, and educators with accurate test data necessary for curricular and administrative decisions (Erford and Moore-Thomas 2004).

Unfortunately, the educational system is largely remiss in teaching children basic socioemotional knowledge and skills—let alone effective strategies for understanding and self-regulating the emotional stress associated with learning and test-taking (Elias and Arnold 2006; Greenberg et al. 2003; Mayer et al. 2008; Salovey and Sluyter 1997; Zins et al. 2004). To rectify such a fundamental deficiency, it is necessary to deepen our understanding of student test anxiety and to implement effective tools to help students overcome this emotional handicap to learning and performance. This is imperative, given the enormous influence emotions are now known to have on the very aspects of cognition targeted in students by the educational process, as summed up by Immordino-Yang and Damasio:

> Recent advances in neuroscience are highlighting connections between emotion, social functioning, and decision making that have the potential to revolutionize our understanding of the role of affect in education. In particular, the neurobiological evidence suggests that the aspects of cognition that we recruit most heavily in schools, namely learning, attention, memory, decision making, and social functioning, are both profoundly affected by and subsumed within the processes of emotion (Immordino-Yang and Damasio 2007, p. 3).

Responding to this urgent problem, the Institute of HeartMath (IHM) designed an innovative classroom program—TestEdge (Institute of HeartMath 2004)—to teach high school students a set of scientifically-based tools and techniques that empower them to self-regulate test-related anxiety and other emotional impediments to effective academic performance. The program has been successfully implemented in many schools, and several pilot studies have measured associated improvements in standardized test scores and psychosocial functioning (Arguelles et al. 2003).

This report presents the results of an electrophysiological study conducted as part of the TestEdge National Demonstration Study (TENDS). Funded by the US Department of Education and conducted during 2004–2005, TENDS was a large-scale investigation (composed of a number of studies) of the efficacy of the TestEdge program in reducing stress and test anxiety, and improving emotional well-being, quality of relationships, and academic performance in public school students (see Bradley et al. 2007 for details of the methodology and findings[1]). Utilizing a quasi-experimental field research design with pre- and post-intervention panels of measurement, the primary study was an in-depth investigation of tenth grade students ($N = 980$) conducted in two large public high schools in Northern California, with data from student and teacher questionnaires, classroom observations, and student performance on two California standardized tests. The electrophysiological study, described here, was designed as a controlled laboratory experiment, using measures of heart rate variability (HRV) to investigate the degree to which students had learned the emotion self-regulation techniques taught in the TestEdge program. It was conducted on a randomly stratified sub-sample of 136 students from both schools. In addition to providing an independent, objective measure of student stress, test anxiety, and emotional management skills, the electrophysiological data offer a unique window on the effects and benefits of emotion self-regulation at the psychophysiological level.

Approaches to Test Anxiety

The Cognitive Model

Most research on test anxiety, and, correspondingly, most interventions for addressing it, adopt a cognitive perspective in which primacy is accorded to the cognitive processes that influence the anxiety response. Building upon Lazarus's (1966) conception of stress as a "transactional process," Spielberger (1966, 1976) developed a model of test anxiety which distinguished between the stress associated with testing situations (the stressor), the subjective evaluation of the degree of threat posed to the individual (the threat), and the emotional state activated in response to

---

[1] See also Daugherty (2006), Hartnett-Edwards (2006, 2008), Hollingsworth (2007), and Schroeder (2006).

the perceived threat (the anxiety response, which includes worry, negative affects, and physiological activation). Spielberger's premise is that the intensity of the anxiety reaction "will vary as a function of the degree of perceived threat" (Spielberger and Vagg 1995a, p. 6). Thus, because all emotional (and physiological) aspects of the anxiety response are driven by a cognitive assessment of the stressor, it is presumed that by changing his/her thoughts about a potentially threatening stimulus, a student can gain control of the emotions aroused by anxiety, and thereby improve test performance (Spielberger and Vagg 1995b).

However, this presumption belies the omnipresent influence emotions have on virtually all aspects of cognition and behavior (Immordino-Yang and Damasio 2007). Evidence from the neurosciences has shown that emotions often occur *without* the involvement of the cognitive system and, moreover, can significantly affect the cognitive process and its output (LeDoux 1996; LeDoux 1994; Niedenthal and Kitayama 1994). These findings help to explain why interventions focusing primarily on changing thought processes may often fail to create sustained change in underlying emotional patterns.

A Psychophysiological Perspective

In contrast to the cognitive model, the approach to test anxiety in this study is informed by a psychophysiological perspective—one that involves the *whole* body—in which emotions are viewed as central and physiological processes are seen to contribute dynamically to ongoing emotional and cognitive experience (Damasio 2003). As James (1884) realized over a century ago, this means that physiological activity is best understood not simply as a *consequence* of emotional activation, but also as a major and continuous influence in the processes that *determine* our emotional experience (c.f. Damasio 2003; Friedman 2009; Pribram 1967, 1991; Pribram and Melges 1969).

As long suspected by physiologist Claude Bernard (see Lane et al. 2009), recent research shows that among the diverse bodily inputs involved in the process of emotion generation, signals from the heart play a uniquely important role (Lane et al. 2009; McCraty and Tomasino 2006; McCraty et al. 2006; Thayer et al. 2009). Equipped with an independently functioning nervous system (Armour and Ardell 1994) and possessing a far more extensive communication system with the brain than do other major organs (Cameron 2002), the heart operates as a primary and consistent generator of rhythmic information patterns that affect the function of the brain and body as a whole. As shown below, afferent neurological signals from the heart not only affect the autonomic regulatory centers in the brain stem, but also cascade up into higher brain centers involved in emotional and cognitive processing, including the thalamus, amygdala, and cortex. Thus, *information originating from the heart operates as a continuous and dominant influence in the processes that ultimately determine our perceptual and emotional experience* (Lane et al. 2009; McCraty et al. 2006; McCraty and Tomasino 2006; Pribram and Melges 1969; Thayer 2007; Thayer et al. 2009; van der Molen et al. 1985).

The naturally occurring beat-to-beat changes in heart rate, known as *heart rate variability* or HRV, encode information about heart–brain interactions and autonomic nervous system dynamics (Friedman and Thayer 1998a, b; Lane et al. 2009; McCraty et al. 1995, 2006; Thayer and Friedman 1997). As a result, HRV has been used as an objective measure of the regulatory processes involved in affective stability and cognitive function (Appelhans and Luecken 2006; McCraty et al. 2006; Porges 1992a, b; Porges et al. 1994; Thayer and Brosschot 2005; Thayer and Lane 2000; Thayer and Sternberg 2006). Of particular interest is a recent work by Thayer and his colleagues (Thayer et al. 2009), which reviews a number of studies conducted by their group across diverse populations and tasks comparing executive (prefrontal) and nonexecutive-function tasks under both threatening (stressful) and nonthreatening conditions. They report evidence of an important relationship between HRV and cognitive performance—namely, that higher levels of resting HRV were positively related to "superior performance" on tasks requiring executive function (Thayer et al. 2009, p. 11). Also, in a recent study, Segerstrom and Solberg Nes (2007, p. 280) conclude that HRV appears to "index" not only self-regulatory strength and effort—the degree to which an individual can "resist temptation, persist at difficult tasks, or regulate emotion"—but, importantly, self-regulatory fatigue, the failure or inability to act in accord with one's intentions. The ability to maximize self-regulatory strength and effort and to avoid self-regulatory fatigue—burnout—is a skill required when facing a demanding challenge, like taking an important test.

However, beyond the issue of the *amount* of HRV is the question of how HRV waveforms are *patterned*. Research conducted by the Institute of HeartMath and others has also shown an important relationship between the pattern of HRV waveforms (heart rhythm patterns), emotional states, and cognitive function (see the review of studies in McCraty et al. 2006). As shown in the real-time example in Fig. 1, heart rhythm patterns are directly responsive to changes in emotional states (McCraty et al. 1995; Tiller et al. 1996). During the experience of stress and negative emotions, such as anger, frustration, and anxiety, heart rhythms become more erratic and disordered—*incoherent* (Fig. 1). In such states, the corresponding patterns of neurological signals traveling from the heart to the brain produce a desynchronization of brain and nervous system activity, which in turn *inhibits* higher cognitive functions (see Fig. 2) and also *reinforces* feelings of emotional stress

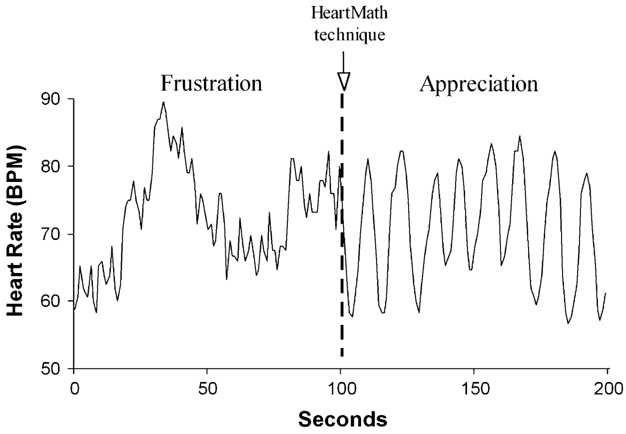

Fig. 1 Heart rhythm patterns in different emotional states. The real-time heart rate variability (heart rhythm) pattern is shown for an individual making an intentional shift from a self-induced state of frustration to a feeling of appreciation by using a HeartMath positive emotion refocusing technique (at the *dotted line*). Note the immediate shift from an erratic, disordered (incoherent) heart rhythm pattern associated with frustration and emotional stress to a smooth, harmonious, sine wave-like (coherent) pattern as the individual uses the positive emotion refocusing technique to self-generate a feeling of appreciation. [Adapted from Bradley et al. (2007, Chapter III). © Institute of HeartMath]

and instability (McCraty and Tomasino 2006; McCraty et al. 2006). Thus, when students come to school or enter a test-taking situation with high levels of anxiety, the "inner noise" produced by such emotional flux impairs the very cognitive resources needed for attention, memory, and effective academic performance (Arguelles et al. 2003; Bradley et al. 2007; Hartnett-Edwards 2008; McCraty 2005).

Conversely, sustained positive emotions, such as love, appreciation, and compassion, are associated with a highly ordered, sine wave-like heart rhythm—a *coherent* pattern (Fig. 1). This reflects greater synchronization between the two branches of the autonomic nervous system and increased physiological efficiency, as described in the following section. This is likely the physiological basis of the well-established relationship between positive emotions and enhanced cognitive function and task performance, including improved perception, attention, memory, decision-making, creativity, and problem-solving (e.g., Fredrickson 2002; Isen 1999). Evidence suggests that when the heart transmits such a coherent signal to the higher brain centers (Fig. 2), higher mental faculties and emotion regulation abilities are facilitated, typically producing greater emotional stability and improved cognitive acuity and task performance (reviewed at length in McCraty et al. 2006; see also McCraty and Tomasino 2006; McCraty et al. 1998). *This is a particularly important point in understanding the operative mechanism of the emotion regulation techniques taught in the TestEdge program.*

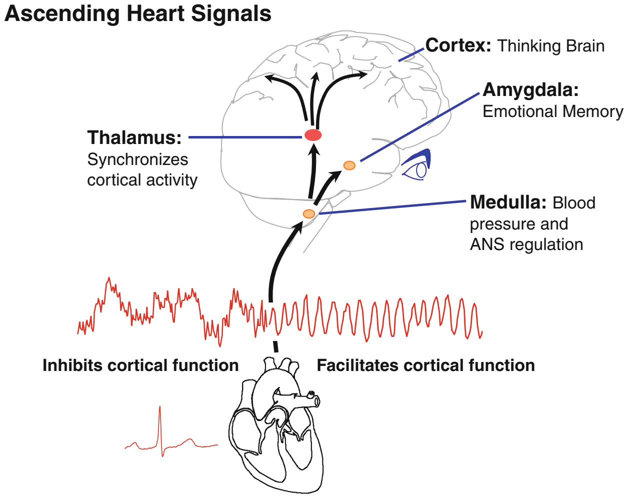

Fig. 2 Heart activity affects brain function. This diagram illustrates the afferent (ascending) pathways by which neurological signals generated by the heart are transmitted to key centers in the brain. These heart signals not only impact autonomic regulatory centers in the brain (e.g., the medulla), but also cascade up to higher brain centers involved in emotional and cognitive processing, including the thalamus, amygdala, and cortex. Through these pathways, heart activity exerts a continuous impact on numerous aspects of brain function. As shown, when patterns of heart activity are erratic and disordered, such as during emotional stress, the corresponding patterns of neurological signals traveling from the heart to the brain produce an *inhibition* of higher cognitive and emotional functions. In contrast, the more ordered and stable pattern of the heart's input to the brain during positive emotions has the opposite effect—serving to *facilitate* cognitive function and reinforcing positive feelings and emotional stability. [Adapted from McCraty et al. (2006). © Institute of HeartMath]

Psychophysiological Coherence

The research described above has led to the characterization of a distinct state—termed *psychophysiological coherence*—associated with the activation of sustained positive emotions. The coherence state encompasses a system-wide shift toward increased order, synchronization, and harmony in physiological and psychological processes. Physiological correlates of this state include: generation of a smooth, sine wave-like HRV waveform oscillating at a frequency around 0.1 Hz (heart rhythm coherence); increased synchronization between the two branches of the autonomic nervous system; decreased sympathetic nervous system activation and increased parasympathetic activity; increased heart–brain synchronization (the brain's alpha rhythms exhibit greater synchrony with the heartbeat); increased vascular system resonance; and entrainment between diverse physiological oscillatory systems (McCraty et al. 2006; Tiller et al. 1996).

These physiological changes generate a highly efficient state in which the body, brain, and nervous system operate

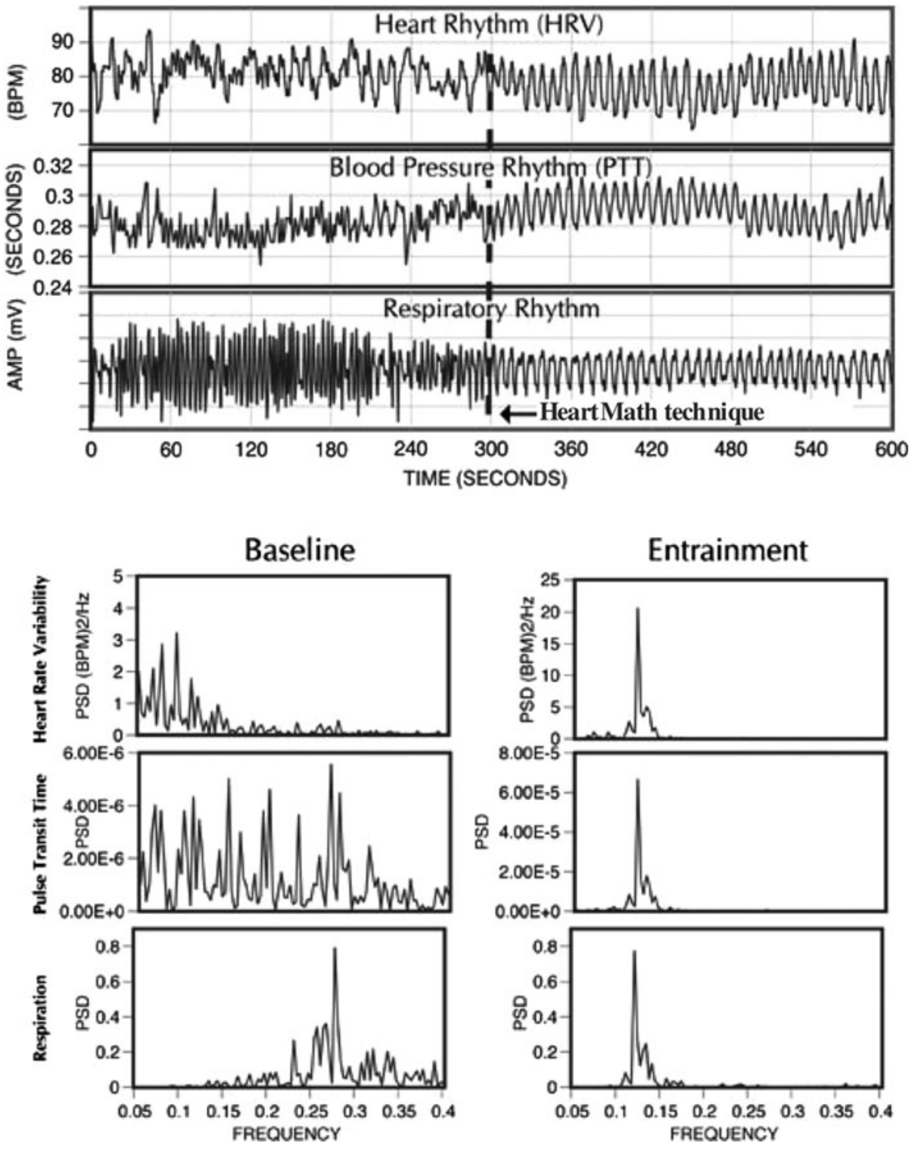

Fig. 3 Entrainment during psychophysiological coherence. These real-time recordings show an individual's heart rhythm activity (heart rate variability pattern), pulse transit time (a measure of beat-to-beat blood pressure), and respiration rhythms over a 10-min period. At the 300-s mark, the individual used a HeartMath emotion self-regulation technique to activate the psychophysiological coherence state, causing these three physiological systems to come into entrainment. The *bottom graphs* show the frequency spectra of the same data on each side of the *dotted line* in the *center* of the *top graph*. Notice the *graphs* on the *right* show that all three systems have entrained to the same frequency (~0.12 Hz). [Adapted from Tiller et al. (1996). © Institute of HeartMath]

with increased synchronization and harmony (Fig. 3). Thus, increased psychophysiological coherence has also been found to directly correlate with measures of cognitive function and task performance—improvements in focus and attention, speed and accuracy of response, and long-term memory (McCraty et al. 2006). At the affective level, the coherence state is associated with greater emotional stability, a reduction in the perception of stress and negative emotions, and an increase in the experience of sustained positive emotions (McCraty et al. 1998, 2006; McCraty and Childre 2004; Tiller et al. 1996).

An important discovery by Childre (Childre and Martin 1999) is that psychophysiological coherence is a state that can be *intentionally generated*. This shift to coherence can be achieved by using a self-regulatory system of positive emotion-based tools and techniques (Childre and Martin 1999; Childre and Rozman 2005), described below. Typically the shift to coherence induces enhancements in perception and cognition that enable more effective reasoning, memory, decision-making, and purposeful action when confronted with stressful or challenging situations. Moreover, with regular practice of coherence-building techniques, these more efficient and harmonious physiological, emotional, and cognitive patterns become increasingly familiar to the brain, ultimately feed-forwarding to a new *set-point* by which the system then strives to *maintain* these healthy patterns of psychophysiological function through a feed-forward process (McCraty and Tomasino 2006; see also Pribram 1991). Evidence of such a psychophysiological "repatterning" process is provided by studies in diverse populations, which have documented enduring improvements in health, hormonal balance, psychological well-being, and socioemotional function in individuals who used coherence-building tools over several months' time (e.g., McCraty et al. 1998, 2003; Luskin et al. 2002; McCraty et al. 2009).

Other research supports the efficacy of this approach in educational settings, where HeartMath programs have improved emotional stability, psychosocial functioning, learning, and academic performance in students at different grade levels (Arguelles et al. 2003; Bradley et al. 2007, 2009; Hartnett-Edwards 2008; McCraty 2005; McCraty et al. 1999). Of direct relevance to the present study is a controlled laboratory experiment with middle school students using electrophysiological measures of HRV. Results showed that students learned to self-activate the coherence state and were able to effectively apply this skill during a stressful or challenging situation (McCraty et al. 1999).

Research Design and Methods

Research Sites and Participants

Conducted over the 2004–2005 academic year, the larger study focused on an in-depth investigation of students at the 10th grade level in two large high schools in Northern California. The school sites were chosen based on their relatively similar sociodemographic characteristics, willingness to participate, and adequate sample size for the study. One high school was randomly selected as the intervention school, to receive the TestEdge program, while the other served as a wait-list control—receiving the intervention program the following academic year, after all data were gathered. Students in both schools took two state-mandated high-stakes exams during the course of the study period: the California High School Exit Exam (CAHSEE) in March 2005 and the California Standards Test (CST) in April 2005. All quantitative and qualitative measurements were conducted in both the experimental and control schools during the same time periods. (For a detailed description of the larger study's methodology and findings, see Bradley et al. 2007.)[2]

As detailed below, the electrophysiological study was designed as a controlled laboratory experiment simulating the stressful conditions of taking a standardized academic test. Students completed an experimental procedure that included a computerized version of the Stroop color-word conflict test (a standard protocol used to induce psychological stress), while continuous HRV recordings were gathered.

To select students for the stress experiment from the whole study population of tenth grade students in both schools, we employed a two-step random-stratified sampling procedure. First, a pool of potential participants from the intervention and control schools was identified, using the following criteria in an effort to construct equivalent experimental and control group samples: equal numbers of students in the high and low test anxiety categories; equal representation by gender; equal distribution among teachers and classrooms; and an equal representation of students in advanced and regular academic level classes. After the pool of potential participants was identified, 136 students were randomly selected; we intentionally over-sampled well beyond our original sample target of 100 participants to provide a buffer for expected attrition over the intervention period. To recruit experiment participants, students were offered the inducement of two free passes to a local movie theater in exchange for their participation: one pass for pre-intervention participation, and a second pair for post-intervention participation. A signed parental permission form was required from each participant. Seventy-seven students from the intervention site and fifty-nine from the control site were recruited for participation in the physiological study.

The Intervention

The intervention consisted of three primary components involving both teachers and students in the intervention school: the Resilient Educator program for teachers; the TestEdge program for students; and heart rhythm coherence biofeedback training for teachers and students (details in Bradley et al. 2007). The goal of the intervention was to teach both teachers and students a set of positive emotion-focused techniques to manage stress and test anxiety. Briefly, these techniques couple an intentional shift in attention to the physical area of the heart with the self-activation of a positive emotion, such as love, compassion, or appreciation. This rapidly initiates a distinct shift to increased coherence in the heart's pattern of rhythmic activity. In turn, this produces a change in the pattern of afferent cardiac signals sent to the brain, which reinforces the self-generated positive emotional shift and makes it easier to sustain.

Resilient Educator

At the intervention school, the tenth grade English Language Arts teachers attended a 1-day Resilient Educator professional development program several months before they were to begin teaching the TestEdge program to their students. This was to give them ample time to practice and achieve a working familiarity with the program's tools and

---

[2] Institutional Review Board (IRB) approval for this project was obtained through Claremont Graduate University, Claremont, California. Parental and student consent were obtained for all students participating in the study.

techniques. In addition to information on the scientific basis of the techniques, the program provides instruction in several of the HeartMath emotion self-regulation and coherence-building techniques, a series of exercises on how to apply them in the classroom and in daily life, and instruction on a computer-based heart rhythm monitor and coherence-building training system—the Freeze-Framer Interactive Learning System (now the emWave Stress Relief System), which each teacher in the program was given for personal use at home and in the classroom. Approximately 3 months later, the teachers attended a second 1-day training workshop to help familiarize them with the specific concepts and techniques they would teach their students in the TestEdge program.

TestEdge

In the experimental school, the TestEdge program was delivered by the English teachers (typically two lessons per week) during the normal class period for one semester, starting in January and ending in May. The program teaches students how to apply coherence-building tools and technologies: in test preparation and test-taking; to increase retention and relevance of academic material; to increase emotional self-awareness; and to more effectively handle stress and challenges, both at school and in their personal lives. The students were also taught how to use the Freeze-Framer Interactive Learning System (described next) and given the opportunity to practice with this technology both in and outside of class.

Heart Rhythm Coherence Feedback

Both the teacher and student programs described above incorporated training with the Freeze-Framer Interactive Learning System,[3] a unique computer-based heart rate variability biofeedback system, designed to facilitate learning and use of the emotion self-regulation and anxiety reduction techniques. Using noninvasive measurement of the pulse, the system displays the user's changing heart rhythm patterns (HRV) in real time and quantifies the level of heart rhythm coherence achieved—the marker of the psychophysiological coherence state. This technology has been used effectively in educational settings by students of diverse sociocultural backgrounds and academic levels (McCraty 2005). The system was installed in the intervention school's three computer labs, one of which was located in the school library to afford students additional opportunity to practice with the system before or after school.

Measures and Data Collection

While extensive quantitative and qualitative data were gathered for the primary study using survey questionnaires, interviews, structured observation, an assessment of student drawings, and student test scores from two California standardized tests, only the data from the Student Opinion Survey and the test scores were combined with physiological data gathered in the stress experiment, which is our focus here.

Student Opinion Survey

The Student Opinion Survey (SOS; Bradley and Atkinson 2004) contains 80 items, psychometrically pre-tested and validated in a pilot study of 96 ninth grade students at a high school in Southern California during the Summer of 2004 (Schroeder 2006). The questionnaire measures student sociodemographic characteristics and fourteen multivariate constructs covering a broad range of students' perceptions of their relationships and connections to teachers, peers, family, and school; positive and negative affect; emotional discord; ability to manage stress; and level of test anxiety (see Table 1). All of the items in the SOS constructs have a Likert-scale response format, and, with one exception, have a 4-point ordinal scale metric; the exception is Feelings About School, which has a 5-point ordinal scale metric. Twelve items measuring four constructs (Feelings About School, Teacher Support, Educational Plans,[4] and Parental Support) were used—with permission—from the California Healthy Kids Survey (California Department of Education 2003). Test anxiety was measured by eight items from the Spielberger's 16-item Test Anxiety Inventory (Spielberger 1980), representing both the "Worry" and "Emotionality" constructs.[5]

---

[3] Since the time of this study, the Freeze–Framer system has been updated and renamed the emWave Stress Relief System.

[4] The three items constituting Educational Plans were not included in the analysis that follows due to a low reliability of measurement coefficient (Cronbach's alpha = 0.47).

[5] The Test Anxiety Inventory (TAI), developed by Charles Spielberger, is the most commonly used validated self-report instrument for measuring test anxiety and has been utilized in the majority of more recent studies of student test anxiety. The TAI provides a global measure of test anxiety as well as a separate measurement of two theoretically relevant components defined as "worry" and "emotionality." The "Worry" construct, which has been found to be most strongly correlated with depressed test performance in students with high test anxiety (Cizek and Burg 2006, p. 17), is essentially a measurement of the psychological aspects of test anxiety (i.e., thought processes and emotions relating to the fear of testing and dread regarding the potential for negative evaluation or failure). The "Emotionality" construct provides a measure of the physical symptoms of test anxiety (e.g., nervousness, sweating, fidgeting, etc.).

Table 1 Psychometric properties of the student opinion survey (SOS) scale constructs [baseline measurement, larger study—entire sample (usable $N = 749$)]

SOS scales	No. of items	Min–max score	Mean	SD	SEM	Cronbach's alpha (α)	Item classification: factor analysis/nominal classification
Test anxiety-global[a]	8	1–4	2.39	0.89	0.03	0.92	8/8
Test anxiety-worry[a]	4	1–4	2.39	0.92	0.03	0.87	4/4
Test anxiety-emotional[a]	4	1–4	2.40	0.96	0.04	0.90	4/4
Feelings about school[b]	3	1–5	3.63	0.71	0.03	0.62	3/3
Teacher support[c]	3	1–4	2.93	0.79	0.03	0.84	3/3
Life preparedness[c]	3	1–4	3.06	0.70	0.03	0.80	3/3
Parental support[c]	4	1–4	3.51	0.65	0.02	0.81	4/4
Positive class experience[c]	4	1–4	2.92	0.68	0.03	0.80	4/4
Extent of friendship[a]	7	1–4	2.98	0.69	0.03	0.86	7/7
Positive affect[a]	7	1–4	2.78	0.62	0.02	0.82	5/7
Negative affect[a]	6	1–4	2.13	0.70	0.03	0.86	6/6
Emotional discord[a]	5	1–4	2.17	0.73	0.03	0.80	3/5
Interactional difficulty[a]	5	1–4	1.93	0.61	0.02	0.72	3/5
Stress management[a]	10	1–4	2.37	0.62	0.02	0.85	9/10

Notes: Item response categories and score values

[a] "Almost Never" (1), "Sometimes" (2), "Often" (3), "Almost Always" (4)

[b] "Strongly Disagree" (1), "Disagree" (2), "Neither Disagree Nor Agree" (3), "Agree" (4), "Strongly Agree" (5)

[c] "Not at all True" (1), "A Little True" (2), "Pretty Much True" (3), "Very Much True" (4)

The SOS questionnaire was completed by students twice: first, early in January of 2005 to obtain a baseline measurement, and again in May, 2 weeks after students took the final high-stakes standardized exam (the CST). In addition, the test anxiety section of the questionnaire was administered as a separate form two additional times: 1 week before students took the CAHSEE in March and 1 week prior to the CST in April.

Using the baseline data for the entire sample from the larger study (usable $N = 749$), an analysis of measurement reliability and validity was conducted with Cronbach's alpha (α) and factor analysis to evaluate the internal consistency and convergent/discriminant validity of each construct. As the alpha coefficients show in Table 1, twelve of the SOS scales achieved or exceeded the technical criterion for measurement adequacy ($\alpha \geq 0.80$), ranging from 0.80 for Life Preparedness, Positive Class Experience, and Emotional Discord, to 0.92 for the Test Anxiety–Global scale. The other two scales had alpha coefficients of 0.72 (Interactional Difficulty) and 0.62 (Feelings About School). The results of a factor analysis performed on the 73 items involved (with varimax rotation and Kaiser normalization; not shown) found that, with the exception of seven items, the statistical classification of items into factors was identical to their nominal assignment as SOS constructs for ten of the fourteen scales (Table 1). In short, the SOS scales were found to be psychometrically valid and reliable measures of the constructs used in the analysis below.[6]

Test Performance

To measure test performance, students' scores from the 2004 CAHSEE and the 2005 CST in English-Language Arts and Mathematics were obtained for both the intervention and control schools. The CST 2004 was designated as the pre-intervention test score variable, and the CST 2005 was designated as the post-intervention test score variable.

Electrophysiological Measures

Continuous HRV recordings were gathered by noninvasive measurement of the pulse throughout the 15–20 min period required to administer the stress experiment's protocol. From the interbeat interval data, a number of standard indices of HRV and a measurement of heart rhythm coherence—the key marker of the psychophysiological coherence state—were derived. The specific measures analyzed were: RR interval (heart rate), standard deviation of RR intervals, high frequency power, low frequency power, total power,

---

[6] See Bradley et al. (2007) (http://www.heartmath.org/research/scientific-ebooks.html) for the SOS instrument (Appendix 3, pp. 329–335) and for the details of the analysis of construct reliability and convergent and discriminant validity (pp. 69–76).

and coherence ratio. The technical details of the processing of the raw HRV data and calculation of these measures are described in the Technical Appendix.

Experimental Protocol and Procedures

On the day of the experiment, students were escorted from their respective classes by a research team member to a designated location where the experiment was conducted. Each student was asked if he or she was color-blind; this was necessary as the computer task students were to perform involved color recognition/discrimination.[7] Each student was then assigned to a station equipped with a laptop computer and was connected to an optical earlobe sensor to measure his/her pulse. Each participant's pulse was continuously recorded (Biopac MP 30) at a sample rate of 250 Hz throughout the entire experimental protocol (approximately 20 min); these pulse data were used to calculate heart rate variability (HRV) and heart rhythm coherence levels, as described in the Technical Appendix.

The analysis that follows focuses on data from two specific phases of the experiment: the *resting baseline* period and the *stress preparation* period. In the resting baseline period of 4 min, during which baseline HRV data were collected, students were asked to sit quietly and to refrain from talking, moving, falling asleep, or engaging in any specific technique or practice. The baseline period was followed by a stress preparation phase of 4 min. Here, to simulate the conditions of a stressful testing situation, students were told that the next phase of the experiment involved measuring their speed and accuracy on a computer task and that they would be given an extra reward if they performed well. Thus, for this 4-min period preceding the computer task, they were instructed to quietly prepare themselves. During the pre-intervention (Time 1) administration, students at both schools were instructed to: "prepare yourself for this performance task by doing what you normally do whenever you are feeling stress about an important upcoming activity, like taking an important test." This stress preparation period was followed by computer administration of four sections of the Stroop Color-Word Conflict Test. Students were asked to do their best and were told that their scores would be compared to those of students in another school. They were presented with instructions for each segment of the Stroop Test in written form on the computer screen as well as hearing the instructions read aloud from a prepared script by one of the researchers.

The post-intervention (Time 2) protocol for the experimental school site differed only in that during the stress preparation phase, students were asked to prepare themselves for the computer task by practicing one of the positive emotion refocusing techniques they had learned in the TestEdge curriculum. The technique is designed to induce a shift into the psychophysiological coherence state through self-activation of a positive emotion (Childre and Rozman 2005; Institute of HeartMath 2004). Students were reminded of the steps of the technique by one of the researchers. For the Time 2 protocol at the control site, students again were asked to use their own methods to prepare themselves for the computer task.

Analysis and Results

Sample Description

Table 2 presents descriptive data on the sample of students who participated in the study and compares the character-

Table 2 Electrophysiological study sample: social characteristics by intervention status

	Entire sample $N = 136$	Experimental $N = 77$	Control $N = 59$
Age, years (mean, SD)	15.3, 0.45	15.3, 0.44	15.3, 0.44
Gender			
Male	47%	53%	40%
Female	53%	47%	60%
Ethnicity			
Caucasian	48%	39%	59%
Hispanic	32%	52%	7%
Asian	12%	3%	24%
Other	4%	5%	3%
African American	1%	0%	2%
Pacific Islander	1%	0%	3%
American Indian	1%	1%	2%
Family composition			
Both biological parents	61%	64%	59%
Single bio parent	15%	13%	17%
Mixed family, one bio parent	12%	14%	9%
Dual custody	9%	8%	10%
Relatives	1%	0%	2%
Other	2%	1%	3%
Class academic level			
Regular class	60%	78%	37%
Advanced class	40%	22%	63%

---

[7] While a behavioral screening of student color vision deficiency would have been more ideal, logistical considerations made this difficult to implement, along with all of the other elements of the protocol, in a manner that would minimize the experiment's intrusion on student class time. However, perusal of the Stroop test results showed no instances of sufficiently poor student performance to suggest that any student participating in the experiment suffered this problem.

istics of participants in the experimental and control schools. Of the 136 students recruited for the physiological study, 77 (56.6%) were in the experimental school and 59 (43.4%) were in the control school. In terms of social characteristics, the experimental and control groups were comparable in age (mean age in both was 15.3 years) and generally similar in family composition, with approximately 60% from an intact family living with both biological parents. However, there were some differences in gender, ethnicity, and class academic level. Whereas there was an almost even division between males and females in the experimental group (53% and 47%, respectively), there was a greater proportion of females in the control group (60% vs. 40%). Reflecting the ethnic characteristics of each school, 39% of students in the experimental group were Caucasian, 52% Hispanic, and 3% Asian; by contrast, in the control group 59% were Caucasian, 7% were Hispanic, and 24% were Asian. Finally, while most students in the experimental group were in a regular class (78% vs. 22%), the majority of the control group were in an advanced class (63% vs. 37%, respectively). This notable difference in academic class level was the result of unanticipated conflicts in student class schedules with the prearranged time for the experiment, and thus compromised the effort to select equivalent experiment and control group samples on academic ability for the physiology study.

With regard to the baseline data on test anxiety, the SOS scales, and test performance, results from an analysis of variance (ANOVA) revealed some significant differences between the groups (Table 3). First, reflecting the sample selection difficulty just mentioned, in terms of effect size (ES), there was a large, significant difference of 46 points in 9th grade mean CST English-Language Arts test scores favoring the control group over the experimental group (394.68 vs. 348.33, ES 0.89, $p < 0.001$). Also, the control group students were more positive in their Feelings About School (3.81 vs. 3.44, ES 0.52, $p < 0.05$) and reported a greater Extent of Friendship (3.14 vs. 2.87, ES 0.41, $p < 0.05$) than the experimental group. It is likely that these differences may be due to the higher proportion of students at the control school who were in an advanced academic class.

Pre-Intervention (Time 1) Results

Resting Baseline Phase

With one important exception—the Standard Deviation of RR Intervals—the results from an ANOVA (not shown) of the HRV measures during the resting baseline period, when students were sitting quietly waiting for the experiment to begin, found that there were no other differences between the two groups of students. The standard deviation of interbeat intervals (SD of RR Intervals) is a global measure of the overall amount of HRV. The difference between the two groups was of a moderate effect size and indicates that the overall amount of HRV in the experimental group was significantly lower than that of the control group (57.38 vs. 66.18, ES 0.41, $p < 0.05$). As discussed above, lower HRV is considered a psychophysiological marker of less than optimal cognitive function, impaired emotional regulation, and core regulatory functions in the development and maintenance of normal behavioral patterns. Although the majority of the behavioral research has focused on younger

Table 3 Time 1—ANOVA of test anxiety, test performance, and SOS scales by intervention status

	Experimental group ($N = 50$)			Control group ($N = 48$)				F	$p<$	ES
	Mean	SD	SEM	Mean	SD	SEM	Mean sq.			
CST English-language arts 9	348.33	49.88	7.35	394.68	54.78	7.99	49952.99	18.18	0.001	0.89
Test anxiety-global	2.56	1.18	0.17	2.32	1.12	0.16	1.46	1.10	ns	0.21
Test anxiety-worry	2.60	1.20	0.17	2.30	1.12	0.16	2.18	1.62	ns	0.26
Test anxiety-emotional	2.52	1.20	0.17	2.33	1.17	0.17	0.87	0.61	ns	0.16
Feelings about school	3.44	0.66	0.09	3.81	0.74	0.11	3.27	6.60	0.05	0.52
Teacher support	2.86	0.74	0.11	3.08	0.73	0.11	1.15	2.10	ns	0.29
Life preparedness	3.10	0.65	0.09	3.01	0.68	0.10	0.18	0.41	ns	0.13
Parental support	3.55	0.70	0.10	3.49	0.60	0.09	0.07	0.16	ns	0.08
Positive class experience	3.02	0.65	0.10	3.10	0.57	0.08	0.15	0.39	ns	0.13
Extent of friendship	2.87	0.74	0.11	3.14	0.61	0.09	1.86	3.98	0.05	0.41
Positive affect	2.87	0.67	0.10	2.74	0.65	0.09	0.41	0.92	ns	0.19
Negative affect	2.23	0.71	0.10	2.19	0.67	0.10	0.03	0.06	ns	0.05
Emotional discord	2.13	0.74	0.10	2.24	0.82	0.12	0.29	0.48	ns	0.14
Interactional difficulty	1.91	0.61	0.09	1.90	0.54	0.08	0.00	0.00	ns	0.01
Stress management	2.51	0.77	0.11	2.47	0.64	0.09	0.04	0.07	ns	0.06

children and adults, two studies with a population near the age studied here found that low HRV was associated with both externalizing and internalizing disorders (Mezzacappa et al. 1997; Pine et al. 1998). This suggests that the students in the experimental group were starting the study in a disadvantaged position, relative to the control group, which was also reflected in their lower test scores.

Stress Preparation Phase

In the Time 1 stress preparation segment of the protocol, the students were instructed to prepare themselves to perform the upcoming computer task quickly and accurately by doing whatever it is they normally do to prepare themselves for a stressful task or challenge, such as taking an important test. An ANCOVA of the students' HRV during this period, in which the resting baseline HRV measures were used as the covariate to control for baseline differences (not shown), found that there were no significant differences between the two groups during this phase of the experiment. This was as expected, since this was prior to the introduction of the TestEdge intervention in the experimental school.

Post-Intervention (Time 2) Results

Resting Baseline Phase

After the completion of the TestEdge intervention in May, the experiment was repeated (Time 2) using exactly the same protocol as described for Time 1. As before, a 4-min resting baseline period, during which the students were sitting quietly, was recorded. The results of an ANCOVA conducted on pre–post changes in the resting baseline period are presented in Table 4.

There were a number of significant differences of mostly a large effect size (ES ≥ 0.50) between the two groups. The first is an increase in the experimental group's overall baseline heart rate variability, as indicated by the larger standard deviation of the inter-beat intervals and increased total power. The pre-intervention difference, favoring the control group, was reversed following the intervention, with the students in the experimental group now showing markedly greater HRV as compared to those in the control group (SD of RR Intervals 72.35 vs. 55.47, ES 0.64, $p < 0.001$; Total Power 1006.89 vs. 501.72; Ln Total Power 6.54 vs. 6.00, ES 0.64, $p < 0.001$). This indicates that a large pre–post improvement in autonomic nervous system function occurred in the experimental group. Also of interest, as physiological indicators of the stress response, are the significant differences in mean heart rate, high frequency power, low frequency power, and coherence ratio. All of these measures indicate mostly large improvements in the students in the experimental group over those in the control group. Thus, the mean heart rate was lower in the experimental group (75.38 vs. 79.62 BPM), and high frequency power (an indicator of parasympathetic activity), was significantly higher (Ln HF Power 5.46 vs. 4.93, ES 0.58, $p < 0.001$). Low frequency power was also higher (Ln LF Power 5.68 vs. 5.15, ES, 0.55, $p < 0.01$), as was the ratio of heart rhythm coherence (Ln Coherence Ratio 3.63 vs. 2.79, ES, 0.52, $p < 0.05$). This last finding is particularly noteworthy, as it suggests that the students had internalized the coherence state as a

Table 4 Time 2—ANCOVA of pre–post resting baseline phase HRV measures by intervention status

	Experimental group					Control group					Mean sq	*F*	*p*<	ES
	N	Mean	SD	Adjusted means	SEM	*N*	Mean	SD	Adjusted means	SEM				
Heart rate	50	76.04	10.12	75.38	1.14	48	78.92	10.35	79.62	1.17				
RR interval	50	809.03	106.71	817.27	11.59	48	777.89	102.51	769.31	11.83	55420.70	8.32	0.01	0.46
Standard deviation of RR intervals	50	68.80	30.91	72.35	2.92	48	59.17	21.78	55.47	2.98	6683.74	15.99	0.001	0.64
High frequency power	50	320.10	315.74	340.17	30.58	48	221.32	208.64	200.41	31.22				
Ln (high frequency power)	50	5.40	0.87	5.46	0.10	48	4.99	0.95	4.93	0.10	6.87	13.77	0.001	0.58
Low frequency power	50	499.01	838.14	538.63	80.99	48	262.91	197.34	221.63	82.69				
Ln (low frequency power)	50	5.60	1.04	5.68	0.12	48	5.24	0.92	5.15	0.12	6.84	9.93	0.01	0.55
Total power	50	925.07	1168.48	1006.89	104.00	48	586.94	387.88	501.72	106.17				
Ln (total power)	50	6.45	0.81	6.54	0.10	48	6.09	0.86	6.00	0.10	6.88	15.55	0.001	0.64
Coherence ratio	50	144.37	286.48	145.68	30.70	48	48.98	98.11	47.61	31.34				
Ln (coherence ratio)	50	3.62	1.81	3.63	0.23	48	2.79	1.45	2.79	0.23	17.29	6.67	0.05	0.52

ANCOVA, resting baseline HRV measure as covariate new, familiar psychophysiological reference state, or set-point. This objective physiological marker suggests that a substantial number of students had likely practiced the coherence-building tools in their daily lives.

Stress Preparation Phase

For the stress preparation phase of the experiment, students in the control group were given the same instruction as in the pre-intervention (Time 1) experiment, and asked to prepare themselves for the performance task by "doing what you normally do whenever you are feeling stress about an important upcoming activity, like taking an important test." During this period, students in the experimental group were instructed to use an emotion self-regulation technique that they had learned in the TestEdge program to prepare themselves for the upcoming computer task. Table 5 presents the results of an ANCOVA, using the Time 1 resting baseline HRV as the covariate.

Significant pre–post differences of mostly a large effect size were observed between the two groups on all measures of HRV. Students in the experimental group had a lower mean heart rate (76.21 vs. 79.62 BPM), suggesting that they were less stressed and had greater high frequency power (Ln HF Power 5.59 vs. 4.93, ES 0.72, $p < 0.001$), indicating a higher level of parasympathetic activity, which is consistent with the lower heart rate. Their low frequency power was also much larger (809.23 vs. 289.70; Ln LF Power, 6.17 vs. 5.37, ES 0.82, $p < 0.001$) which, when combined with the increased high frequency power, indicates that they were in a more relaxed, yet energized state associated with the psychophysiological coherence mode. This interpretation is confirmed by the significantly larger heart rhythm coherence ratio observed in the experimental site students (Ln Coherence Ratio, 4.61 vs. 2.79, ES 1.26, $p < 0.001$). Overall, the HRV data present compelling objective evidence that the students in the experimental group had learned how to shift into the coherence state at will, and were better able to manage their stressful emotions when preparing for a challenging task or situation, such as taking an important test.

Test Anxiety, Test Performance, and Emotional Disposition

Next, we turn to the results of an ANCOVA (not shown) controlling for baseline differences on the post-intervention SOS scales and test performance for the students in the physiological study. Significant pre–post differences of a low to moderate effect size were found on all three measures of test anxiety, whereby mean test anxiety was lower for the experimental group than it was for the control group (TAI-Global 1.94 vs. 2.30, ES 0.37, $p < 0.01$; TAI-Worry 2.03 vs. 2.29, ES 0.26, $p < 0.05$; TAI-Emotionality 1.82 vs. 2.29, ES 0.48, $p < 0.001$). On the SOS scales, a large pre–post difference in Negative Affect favoring the experimental group was observed (2.00 vs. 2.35, ES 0.50, $p < 0.01$). No significant pre–post difference was found on the measure of test performance—9th–10th grade mean score change in CST ELA. This was not unexpected, as a higher proportion of the control group students were from

Table 5 Time 2—ANCOVA of pre–post stress preparation phase HRV measures by intervention status

	Experimental group					Control group					Mean sq	*F*	*p*<	ES
	N	Mean	SD	Adjusted means	SEM	*N*	Mean	SD	Adjusted means	SEM				
Heart rate	50	76.84	10.33	76.21	1.24	48	78.96	10.80	79.62	1.27				
RR interval	50	803.05	108.85	810.95	13.04	48	780.18	113.41	771.96	13.31	36622.26	4.34	0.05	0.35
Standard deviation of RR intervals	50	78.63	32.57	82.38	3.15	48	63.71	24.05	59.80	3.22	11966.53	24.58	0.001	0.80
High frequency power	50	347.12	267.01	366.89	32.16	48	235.26	285.42	214.67	32.83				
Ln (high frequency power)	50	5.53	0.87	5.59	0.10	48	4.99	0.96	4.93	0.11	10.48	19.44	0.001	0.72
Low frequency power	50	772.95	1058.32	809.23	106.93	48	327.50	265.16	289.70	109.17				
Ln (low frequency power)	50	6.10	1.02	6.17	0.13	48	5.44	0.92	5.37	0.13	15.06	19.65	0.001	0.82
Total power	50	1248.80	1269.09	1328.81	122.62	48	711.58	541.81	628.23	125.18				
Ln (total power)	50	6.76	0.87	6.84	0.10	48	6.26	0.85	6.17	0.10	10.62	21.04	0.001	0.77
Coherence ratio	50	364.21	594.18	367.62	60.40	48	30.24	36.51	26.69	61.65				
Ln (coherence ratio)	50	4.61	1.74	4.61	0.21	48	2.79	1.15	2.79	0.22	81.57	36.87	0.001	1.26

ANCOVA, Time 1 resting HRV measure as covariate advanced classes and thus had significantly higher mean test scores at the outset than did students in the experimental group (see Table 3).

Breaking the data out by baseline test anxiety, one of the variables used to stratify sample selection for this study, allows for a closer examination of the impact of the intervention on test anxiety level, emotional disposition, test performance, and HRV measures. Tables 6 and 7 present the results of separate ANCOVAs for students with low and high test anxiety, respectively, by intervention status, while controlling for baseline differences on the other factors.

Starting with the results for the low test anxiety category (Table 6), the only SOS construct showing a significant pre–post change was Teacher Support, which was more favorable in the control group (2.99 vs. 3.32, ES 0.71, $p < 0.05$). At the physiological level, during the resting baseline period there was evidence of an improvement in autonomic function in the experimental group relative to the control group (RR Interval, 816.97 vs. 764.44, ES 0.28, $p < 0.05$; SD of RR Intervals, 66.98 vs. 55.30, ES 0.15, $p < 0.05$; Ln HF Power, 5.48 vs. 4.94, ES 0.49, $p < 0.01$); however, there was no indication of a change in heart coherence.

However, there is evidence during the stress preparation phase that students in the experimental group had learned how to generate heart coherence at will. Thus, on three of the physiological measures there was a significant pre–post change favoring the experimental group (SD of RR Intervals, 76.41 vs. 59.51, ES 0.29, $p < 0.01$; Ln HF Power, 5.50 vs. 4.89, ES 0.50, $p < 0.01$; and Ln Coherence Ratio, 4.45 vs. 3.18, ES 0.84, $p < 0.01$).

With respect to the results for the high test anxiety category (Table 7), the data reveal a stronger pattern of pre–post changes, all with large effect sizes, differentiating the experimental group from the control group. On the SOS constructs, improvements in two of the test anxiety scales and the measure of negative affect were observed for the experimental group (Test Anxiety-Global, 2.57 vs. 3.23, ES 0.85, $p < 0.01$; Test Anxiety-Emotionality, 2.31 vs. 3.26, ES 1.25, $p < 0.001$; Negative Affect, 2.10 vs. 2.60, ES 0.67, $p < 0.01$).

Moving to the physiological data, both for the resting baseline and stress preparation periods, the results are unequivocal: on virtually every HRV measure, the students in the experimental group evidence a clear pre–post change over their peers in the control group. Thus, during the resting baseline period, this is apparent for the measures of overall HRV (SD of RR Interval, 76.21 vs. 56.61, ES 0.50, $p < 0.01$; Ln Total Power, 6.64 vs. 5.93, ES 0.66, $p < 0.01$), for the indicator of parasympathetic function (Ln HF Power, 5.44 vs. 4.92, ES 0.41, $p < 0.05$), and for both low frequency power and heart coherence (Ln LF Power, 5.88 vs. 5.04, ES 0.77, $p < 0.01$; Ln Coherence Ratio, 3.92 vs. 2.46, ES 0.90, $p < 0.01$).[8]

The results were notably stronger, both in terms of statistical significance and effect size, during the stress preparation period, when students in the experimental group were asked to activate one of the emotion self-regulation tools they had learned (SD of RR Interval, 86.98 vs. 60.82, ES 0.70, $p < 0.001$; Ln Total Power, 6.99 vs. 6.08, ES 0.86, $p < 0.001$; Ln HF Power, 5.66 vs. 4.98, ES 0.63, $p < 0.01$; Ln LF Power, 6.34 vs. 5.19, ES 1.06, $p < 0.001$; Ln Coherence Ratio, 4.75 vs. 2.28, ES 1.88, $p < 0.001$).

In short, in relation to the aggregated results presented above, these physiological data show that it was the subset of students in the experimental group who most needed help—those who began the study with high test anxiety and low test performance—who had derived the greatest benefit from the intervention.

Finally, on the question of the impact of the intervention on test performance, results from a matched-pairs analysis provide suggestive evidence for the hypothesized result. The Time 1 differences between the experimental and control groups on test performance, noted at the outset (CST ELA-9, 348.33 vs. 394.68, respectively, ES 0.89, $p < 0.001$), meant that there were insufficient equivalent cases for a standard matched-pairs comparison in which Time 1 scores on text anxiety and test performance, the two primary dependent variables, were matched in each group at Time 1. While it was a less than optimal alternative, we inverted the experimental logic by selecting students from the experimental group who conformed to the expected relationship between test anxiety and test performance, and then matched each with a student from the control group with approximately the same baseline (9th grade CST ELA) test score.[9] This generated 11 matched pairs of students, including one matched-pair involving two students from the control group who had the same test score. We then conducted an ANCOVA to see if the expected pre–post differences between the two groups still remained.

The results of the ANCOVA, showing mostly large, significant differences, are presented in Table 8. Thus on the Test Anxiety-Global scale (1.90 vs. 2.41, ES 0.49, $p < 0.05$) and especially on the Test Anxiety-Emotionality scale (1.68 vs. 2.42, ES 0.69, $p < 0.05$), and a very large

---

[8] The pre–post results of a within-groups paired *t*-test analysis (not shown), performed separately on each of the four subgroups analyzed here (low vs. high test anxiety by intervention status), found that while an improvement in resting baseline HRV measures was observed in both subgroups of the experimental group—especially in the high test anxiety subgroup—these measures had *declined* in both the high and low test anxiety subgroups of the control group.

[9] We matched students to within a range of 5 test score points to each other, as a closer matching was not possible given the frequency distribution of 9th grade ELA scores in the two groups.

Table 6 Time 2—ANCOVA for low test anxiety subgroup: pre–post test anxiety, test performance, SOS scales, and baseline resting and stress preparation HRV measures, by intervention status

	Experimental group ($N = 27$)				Control group ($N = 21$)				Mean sq	F	$p<$	ES
	Mean	SD	Adjusted means	SEM	Mean	SD	Adjusted means	SEM				
Test performance and SOS scales												
CST English-language arts 10	349.57	50.56	375.11	7.37	405.11	60.42	385.25	6.41	978.99	0.98	ns	1.00
Test anxiety-global	1.34	0.38	1.36	0.09	1.43	0.53	1.42	0.08	0.05	0.26	ns	0.18
Test anxiety-worry	1.33	0.40	1.32	0.09	1.43	0.50	1.43	0.08	0.14	0.78	ns	0.21
Test anxiety-emotional	1.36	0.43	1.38	0.12	1.43	0.68	1.42	0.11	0.02	0.06	ns	0.12
Feelings about school	3.51	0.69	3.72	0.10	3.95	0.71	3.77	0.10	0.02	0.08	ns	0.63
Teacher support	2.90	0.81	2.99	0.12	3.40	0.59	3.32	0.11	1.36	4.31	0.05	0.71
Life preparedness	3.10	0.63	3.14	0.11	3.22	0.63	3.19	0.10	0.03	0.10	ns	0.19
Parental support	3.73	0.34	3.72	0.08	3.57	0.44	3.57	0.07	0.25	1.76	ns	0.40
Positive class experience	2.98	0.65	3.11	0.10	3.17	0.69	3.07	0.09	0.02	0.12	ns	0.30
Extent of friendship	2.83	0.69	2.94	0.09	3.05	0.56	2.96	0.08	0.01	0.04	ns	0.37
Positive affect	2.97	0.52	2.96	0.11	2.83	0.64	2.84	0.10	0.19	0.76	ns	0.24
Negative affect	1.90	0.55	1.92	0.11	2.14	0.75	2.13	0.11	0.55	1.85	ns	0.38
Emotional discord	1.92	0.67	1.93	0.13	1.99	0.79	1.98	0.12	0.03	0.08	ns	0.09
Interactional difficulty	1.76	0.53	1.76	0.10	1.81	0.55	1.81	0.09	0.03	0.13	ns	0.11
Stress management	2.39	0.59	2.43	0.12	2.54	0.64	2.50	0.11	0.06	0.21	ns	0.23
Resting HRV												
Heart rate	76.56	11.18	75.22	1.90	78.94	9.80	80.08	1.75				
RR interval	803.83	109.63	816.97	18.32	775.63	91.15	764.44	16.87	32426.80	4.33	0.05	0.28
Standard deviation of RR intervals	62.28	20.33	66.98	3.25	59.31	20.38	55.30	2.99	1534.38	6.65	0.05	0.15
High frequency power	289.92	198.84	312.04	34.94	207.18	193.04	188.34	32.20				
Ln (high frequency power)	5.41	0.80	5.48	0.14	5.00	0.84	4.94	0.13	3.56	8.58	0.01	0.49
Low frequency power	284.72	255.65	313.20	41.77	279.71	171.48	255.45	38.42				
Ln (low frequency power)	5.28	0.91	5.43	0.15	5.38	0.82	5.25	0.14	0.34	0.65	ns	0.11
Total power	671.02	449.40	745.17	71.57	601.67	368.32	538.51	65.83				
Ln (total power)	6.28	0.72	6.40	0.13	6.17	0.77	6.07	0.12	1.29	3.60	ns	0.15
Coherence ratio	72.10	94.45	72.11	19.27	56.85	88.82	56.85	17.78				
Ln (coherence ratio)	3.26	1.71	3.32	0.31	3.05	1.45	3.00	0.29	1.26	0.57	ns	0.13
Stress preparation HRV												
Heart rate	77.67	11.96	76.44	2.13	79.59	10.51	80.64	1.97				
RR interval	796.10	117.72	808.86	20.96	772.31	103.16	761.44	19.30	26416.59	2.70	ns	0.22
Standard deviation of RR intervals	71.00	23.71	76.41	3.82	64.11	23.67	59.51	3.51	3213.42	10.10	0.01	0.29
High frequency power	328.20	298.41	361.63	52.83	221.90	293.72	193.43	48.69				
Ln (high frequency power)	5.42	0.93	5.50	0.16	4.96	0.90	4.89	0.14	4.45	7.98	0.01	0.50
Low frequency power	496.17	474.64	530.89	79.42	367.78	287.79	338.21	73.06				
Ln (low frequency power)	5.82	0.91	5.91	0.17	5.63	0.77	5.55	0.15	1.54	2.49	ns	0.23
Total power	928.00	691.36	1027.37	115.71	741.67	558.98	657.03	106.44				
Ln (total power)	6.54	0.82	6.65	0.14	6.36	0.72	6.27	0.13	1.72	4.02	ns	0.24
Coherence ratio	373.05	564.09	373.01	80.60	40.93	43.34	40.96	74.39				
Ln (coherence ratio)	4.46	1.97	4.45	0.33	3.17	1.07	3.18	0.30	19.83	8.11	0.01	0.84

Table 7 Time 2—ANCOVA for high test anxiety subgroup: pre–post test anxiety, test performance, SOS scales, and baseline resting and stress preparation HRV measures, by intervention status

	Experimental group ($N = 27$)				Control group ($N = 21$)				Mean sq	F	$p<$	ES
	Mean	SD	Adjusted means	SEM	Mean	SD	Adjusted means	SEM				
Test performance and SOS scales												
CST English-language arts 10	335.08	42.29	346.32	5.83	373.25	48.92	359.20	6.56	1629.05	2.03	ns	0.84
Test anxiety-global	2.59	0.78	2.57	0.14	3.20	0.66	3.23	0.15	5.10	10.36	0.01	0.85
Test anxiety-worry	2.81	0.81	2.78	0.15	3.14	0.73	3.17	0.17	1.77	3.01	ns	0.44
Test anxiety-emotional	2.31	0.87	2.31	0.15	3.26	0.65	3.26	0.16	10.46	18.70	0.001	1.25
Feelings about school	3.52	0.80	3.57	0.10	3.86	0.63	3.79	0.12	0.55	2.00	ns	0.47
Teacher support	2.94	0.88	2.99	0.14	2.98	0.73	2.92	0.15	0.05	0.10	ns	0.06
Life preparedness	3.02	0.73	2.94	0.12	2.86	0.66	2.97	0.13	0.01	0.03	ns	0.24
Parental support	3.56	0.62	3.51	0.09	3.31	0.66	3.37	0.10	0.21	1.11	ns	0.39
Positive class experience	2.85	0.73	2.85	0.14	2.98	0.64	2.98	0.15	0.21	0.44	ns	0.18
Extent of friendship	2.92	0.79	3.01	0.10	3.31	0.53	3.20	0.11	0.41	1.56	ns	0.58
Positive affect	2.98	0.58	2.91	0.11	2.67	0.80	2.76	0.12	0.28	0.91	ns	0.45
Negative affect	2.11	0.59	2.10	0.12	2.59	0.83	2.60	0.13	2.87	7.86	0.01	0.67
Emotional discord	2.36	0.82	2.46	0.11	2.80	0.78	2.67	0.12	0.49	1.67	ns	0.54
Interactional difficulty	1.88	0.67	1.88	0.11	2.12	0.54	2.12	0.13	0.63	1.93	ns	0.39
Stress management	2.71	0.65	2.65	0.10	2.30	0.72	2.38	0.12	0.83	2.84	ns	0.60
Resting HRV												
Heart rate	75.60	9.32	75.48	1.40	78.90	11.26	79.06	1.59				
RR interval	813.45	106.06	816.63	14.88	780.80	117.80	776.71	16.88	18782.39	3.14	ns	0.29
Standard deviation of RR intervals	74.36	37.17	76.21	4.73	58.99	23.98	56.61	5.37	4491.69	7.47	0.01	0.50
High frequency power	345.81	391.07	361.42	49.93	239.50	230.73	219.43	56.64				
Ln (high frequency power)	5.39	0.95	5.44	0.15	4.97	1.09	4.92	0.17	3.20	5.18	0.05	0.41
Low frequency power	681.55	1092.42	681.61	140.15	241.31	228.96	241.23	158.92				
Ln (low frequency power)	5.86	1.09	5.88	0.18	5.05	1.04	5.04	0.20	8.30	10.09	0.01	0.77
Total power	1141.49	1515.44	1181.68	182.09	568.01	420.16	516.34	206.53				
Ln (total power)	6.60	0.87	6.64	0.14	5.98	0.98	5.93	0.16	5.94	11.17	0.01	0.66
Coherence ratio	205.93	372.24	209.17	56.19	38.85	110.34	34.69	63.78				
Ln (coherence ratio)	3.93	1.86	3.92	0.33	2.45	1.41	2.46	0.37	25.09	8.74	0.01	0.90
Stress preparation HRV												
Heart rate	76.14	8.89	76.02	1.42	78.14	11.37	78.30	1.60				
RR interval	808.98	102.58	811.99	16.45	790.29	127.28	786.43	18.65	7698.81	1.06	ns	0.16
Standard deviation of RR intervals	85.13	37.79	86.98	4.94	63.19	25.11	60.82	5.60	8000.11	12.21	0.001	0.70
High frequency power	363.23	241.72	375.40	39.25	252.43	280.62	236.79	44.53				
Ln (high frequency power)	5.62	0.82	5.66	0.14	5.03	1.05	4.98	0.16	5.53	10.20	0.01	0.63
Low frequency power	1008.72	1339.67	1008.77	186.96	275.71	229.24	275.65	211.99				
Ln (low frequency power)	6.33	1.07	6.34	0.18	5.20	1.06	5.19	0.20	15.64	17.96	0.001	1.06
Total power	1522.07	1569.18	1556.99	207.57	672.88	529.98	627.99	235.43				
Ln (total power)	6.94	0.90	6.99	0.15	6.13	0.99	6.08	0.17	9.71	17.15	0.001	0.86
Coherence ratio	356.69	629.28	362.23	91.92	16.49	18.35	9.37	104.34				
Ln (coherence ratio)	4.75	1.54	4.75	0.26	2.29	1.07	2.28	0.30	71.91	38.28	0.001	1.88
ANCOVA												

Table 8 Matched-pairs ANCOVA of pre–post differences on selected variables and HRV measures during Time 2 stress preparation phase by intervention status

	Experimental group					Control group					Mean sq	*F*	*p*<	ES
	N	Mean	SD	Adjusted means	SEM	*N*	Mean	SD	Adjusted means	SEM				
CST English-language arts 10	11	364.55	49.22	365.54	5.46	12	351.25	49.09	350.34	5.23	1323.87	4.04	=0.058	0.31
Test anxiety-global	11	1.75	0.93	1.90	0.18	12	2.54	1.16	2.41	0.17	1.50	4.39	0.05	0.49
Test anxiety-emotional	11	1.55	0.90	1.68	0.21	12	2.54	1.24	2.42	0.20	3.07	6.70	0.05	0.69
Parental aupport	11	3.80	0.25	3.68	0.14	12	3.13	0.65	3.24	0.13	0.92	4.78	0.05	0.98
Negative affect	11	1.68	0.48	1.79	0.19	12	2.63	0.72	2.53	0.18	2.55	7.28	0.05	1.23
Interactional difficulty	11	1.47	0.24	1.55	0.12	11	2.05	0.42	1.98	0.12	0.62	5.38	0.05	1.31
Physiology measures during stress prep period														
Heart rate	11	76.94	9.01	76.64	2.08	12	81.31	7.72	81.58	2.00	139.54	2.93	ns	0.59
RR interval	11	797.22	92.24	801.50	21.34	12	749.68	71.21	745.76	20.43	17664.46	3.54	ns	0.68
Standard deviation of RR intervals	11	76.78	21.91	77.94	5.92	12	63.91	16.77	62.84	5.66	1228.52	3.30	ns	0.78
High frequency power	11	326.13	197.37	342.48	72.89	12	241.68	294.04	226.70					
Ln (high frequency power)	11	5.54	0.85	5.55	0.25	12	5.05	0.91	5.04	0.24	1.47	2.08	ns	0.58
Low frequency power	11	644.92	603.69	637.98	136.91	12	315.04	198.20	321.41					
Ln (low frequency power)	11	6.11	0.90	6.13	0.26	12	5.53	0.78	5.52	0.25	2.07	2.87	ns	0.72
Total power	11	1077.92	742.78	1112.86	182.46	12	660.08	433.29	628.06					
Ln (total power)	11	6.75	0.77	6.77	0.21	12	6.31	0.64	6.29	0.20	1.29	2.65	ns	0.68
Coherence ratio	11	381.56	437.57	382.64	91.87	12	34.87	51.95	33.88					
Ln (coherence ratio)	11	4.95	1.83	4.99	0.46	12	2.83	1.14	2.78	0.44	27.51	12.13	0.01	1.49
ANCOVA														

difference on heart rhythm coherence (Ln-Coherence Ratio 4.99 vs. 2.78, ES 1.49, $p < 0.01$) during the stress preparation period, favoring the experimental group. In addition, on the SOS scales, the experimental group had significantly lower Negative Affect (1.79 vs. 2.53, ES 1.23, $p < 0.05$) and Interactional Difficulty (1.55 vs. 1.98, ES 1.31, $p < 0.05$), and a significantly increased rating of Parental Support (3.68 vs. 3.24, ES 0.98, $p < 0.05$). There was also a marginally significant difference on 9th–10th grade ELA test performance, in which the experimental group students outperformed their matched-pair equivalents in the control group (365.54 vs. 350.34, ES 0.31, $p = 0.058$).

Discriminant Function Analysis

As a final step in our investigation of the physiological data, we conducted a pre- and post-intervention discriminant function analysis on the full sample of students in the study. We were interested in investigating the degree to which post-intervention changes in test anxiety and psychophysiological coherence distinguished the experimental group students from those in the control group.

Discriminant function analysis is an ideal multivariate statistical procedure for investigating this type of question (Bradley et al. 1993). This is because the procedure aims to construct an additive linear model (the canonical discriminant function), composed of interval-level independent variables, that maximizes the separation (reduces the statistical association) between two or more nominal groups which, together, are treated as the dependent variable. It also provides a measure of the statistical model's predictive power by calculating the model's ability to correctly classify cases into their a priori nominal groupings.

For our analysis, we used the nominal variable, intervention status, as the dependent variable and test anxiety, test performance, the SOS scales, and the measures of HRV as the independent variables. We conducted two sets of analysis: one on the data collected at Time 1, prior to the intervention, and the second on the post-intervention (Time 2) data. And, to investigate the expected pre–post-intervention changes in test anxiety and coherence, we ran separate analyses using the physiological data collected during the resting and stress preparation periods. For all four analyses we used the subset of 98 students who had usable pre and post data.

Pre-Intervention (Time 1) Results

The pre-intervention results for the resting baseline period and stress preparation period were identical (results not shown). Of the 24 variables considered for entry into the statistical model in the stepwise procedure, only one variable, the 9th grade CST ELA test score, had sufficient statistical power for inclusion (min. partial F to enter = 3.84; max. partial F to remove = 2.71). This was not unexpected, given the large difference between the two groups at baseline on the 9th grade CST ELA test scores, previously noted above.

However, the resulting canonical discriminant function produced only a small separation between the experimental and control groups (Wilks' Lambda = 0.848, Chi-square = 14.136, $p < 0.001$), and only explained approximately 18% of the variance (Eigenvalue = 0.180, Canonical Correlation = 0.390). Even so, this model achieved a 67.7% correct classification rate in predicting student membership into their a priori groups, which was significantly different from the 50–50% correct for the two groups expected by chance (binomial test: $p < 0.001$, prior prob. 0.50).

Post-Intervention (Time 2) Results

From the analysis of the post-intervention data, two discriminant function models were generated (results not shown), both of which were consistent with the expected effects of the intervention articulated above. In a notable difference from the pre-intervention discriminant function model, neither model contained the CST ELA test score. Instead, the two models contained measures of test anxiety and HRV.

In more specific terms, the results for the *resting baseline period* showed that two variables met the criteria for entry in the stepwise procedure. The pre–post change in the Standard Deviation of RR Intervals—a measure of the change in HRV parameters—was the first variable entered (Wilks' Lambda = 0.822), and pre–post test anxiety—measuring the change in test anxiety—was the second (Wilks' Lambda = 0.760). Together, they formed a canonical discriminant function which produced a modest separation between the experimental and control groups (Wilks' Lambda = 0.760, Chi-square = 21.962, $p < 0.001$) and explained approximately 32% of the variance (Eigenvalue = 0.316, Canonical Correlation = 0.490). This model achieved a significant 70.1% prediction rate in correctly classifying students into their a priori groups (binomial test: $p < 0.001$, prior prob. 0.50).

The results of the discriminant function analysis for the *stress preparation period* were consistent with the expected effects of the intervention. Three variables—two measures of HRV change and the measure of test anxiety change—met the criteria for entry in the stepwise procedure. The change in low frequency power was the first variable entered (Wilks' Lambda = 0.732), the change in test anxiety was second (Wilks' Lambda = 0.673), and the change in coherence ratio was the third (Wilks' Lambda = 0.641). Together, they formed a canonical discriminant function which produced a moderate degree of separation between the experimental and control groups (Wilks' Lambda = 0.641, Chi-square = 35.385, $p < 0.001$) and explained approximately 56% of the variance (Eigenvalue = 0.561, Canonical Correlation = 0.599). This model achieved a significant 79.4% prediction rate in correctly classifying students into their a priori groups (binomial test: $p < 0.001$, prior prob. 0.50).

Overall, the results from the discriminant function analysis are in line with the expected effects of the TestEdge intervention. These results show that by lowering test anxiety and increasing psychophysiological coherence in the students in the experimental group, the intervention appears to have produced positive changes on these factors, which set them apart from students in the control group.

Discussion

There were a number of important findings from the physiological data which indicate that the students in the intervention group appear to have effectively learned, practiced, and integrated the emotion self-regulation skills taught in the program. Beginning with the results from the stress preparation phase of the experiment—the primary focus of the study, the main finding was that the experimental group's post-intervention heart rhythm coherence ratio was significantly larger than that of the control group, and was also significantly higher than that observed during the resting baseline period. In addition, these students had lower heart rates, and significantly greater high and low frequency power in the HRV power spectrum. This pattern of findings—evident for both low and high test anxiety subgroups—shows that after having completed the intervention, students in the experimental group were able to self-activate the coherence state at will during a stressful testing scenario. This result indicates that these students had attained an effective level of emotional self-regulatory competence through the skills taught in the TestEdge program.

More surprising, and unexpected, were the results observed for these students during the Time 2 *resting baseline period*. During this phase, students were instructed just to sit quietly and naturally. While the aggregated results for the whole experimental group showed significantly increased HRV across all measures, the breakdown by test anxiety category revealed that this change was more pronounced in the high test anxiety subgroup. Despite the fact that they were *not* consciously using the self-regulation tools, these students nevertheless exhibited mostly large increases in HRV and a large increase in heart rhythm coherence during the Time 2 resting baseline phase, when compared with their Time 1 measures. This is a noteworthy finding, as it suggests that a repatterning process likely occurred at a fundamental level, resulting in the instantiation of a healthier, more adaptive pattern of psychophysiological function as a new set-point. Moreover, *this change occurred in the very group of students most in need of help in managing stress—those with high test anxiety and low test performance*.

Considering, first, the change in the magnitude of HRV, which was observed both in aggregate and for each of the low and high test anxiety subgroups, this is a clear indication that an improvement in autonomic nervous system function occurred over the study period in the students in the experimental group. This finding not only signifies an improvement in health status, but it also has important cognitive and behavioral implications, since HRV is considered a psychophysiological marker of cognitive functioning, emotion self-regulation abilities, and core regulatory functions (Appelhans and Luecken 2006; McCraty et al. 2006; Segerstrom and Solberg Nes 2007; Suess et al. 1994; Thayer et al. 2009). Higher HRV reflects increased flexibility and adaptability—both psychologically and physiologically—to environmental demands. Conversely, low HRV, particularly the components reflecting parasympathetic activity, is associated with a loss of inhibitory control of anxiety (Friedman and Thayer 1998a, b; Porges 1992b; Porges et al. 1994; Thayer and Friedman 1997). This is the first study that we know of to show that high school students' HRV can be increased over a relatively short period of time, and that such an improvement in autonomic function can be accomplished through a supplementary classroom program.

Not only had the high test anxiety subgroup's overall HRV increased at the Time 2 resting baseline recording, but their ratio of heart rhythm coherence—the key marker of the psychophysiological coherence state—had also increased, with a notably large effect size (0.90). This finding is further evidence of a repatterning process in this group of students, likely facilitated by their use and consequent internalization of the emotion self-regulation skills they had learned.

Consistent with these electrophysiological results were the changes in emotional disposition observed in the high test anxiety subgroup, as measured by the SOS instrument. There was a significant reduction in feelings of stress, anger, disappointment, sadness, loneliness, and depression (Negative Affect scale), which was accompanied by a large and significant reduction in test anxiety. These findings indicate that the emotion self-regulation tools taught in the program were effective in helping these students to reduce negative emotions generally and, more specifically, to reduce their test anxiety. Given that the coherence state is typically associated with reduced stress, improved cognitive function, and emotional stability (Tiller et al. 1996; McCraty and Tomasino 2006; McCraty et al. 2006), it is likely that the instantiation of this state as a new set-point in the students' physiology helped to support and sustain the associated favourable emotional and behavioral changes observed.

Although a significant increase in test performance in the experimental group was not observed for the full sample in this study, this was is not unexpected, given the small sample size and the disproportionate representation of students from advanced classes in the control group (63% compared to 22% in the experimental group), who began the study with much higher test scores. However, when baseline test scores were matched on 9th grade CST ELA, there was a notable and marginally significant difference in test score gains from 9th to 10th grade in the experimental group, which was associated with a corresponding reduction in test anxiety and improvements in socioemotional measures, and a large increase in heart rhythm coherence during the stress preparation period. While less than definitive, these test performance results are consistent with those in the larger study, which found that subgroups of students in the experimental group—who were matched with students in the control group with comparable characteristics—had both a pre–post-intervention reduction in test anxiety and an improvement in test performance (see Bradley et al. 2007, pp. 129–152).

Finally, results from the discriminant function analysis showed that before the intervention, during both the resting baseline and stress preparation periods, the only differentiator of the students in the two groups was student performance on the 9th grade CST ELA test—a result consistent with the known difference in academic ability between the two schools. However, by the time of post-intervention measurement, test performance was no longer the common differentiator between the two groups of students: it had been replaced by changes in test anxiety and heart rhythm coherence. Not only were these factors effective in discriminating between students in the experimental and control groups during the resting baseline period, but they were an even more powerful discriminator during the stress preparation period—the discriminant function constructed from these factors explained 56% of the variance and achieved a 79% prediction rate in correctly classifying students into their a priori groups.

A final point is the question of causal inference. Although it is possible that some other unmeasured factor/s could be involved, it is reasonable to infer, given the overall pattern of results, that student learning of the program's emotion self-regulation skills is the most plausible explanation for the improvements observed in HRV function, test anxiety, and emotional disposition. However, the results from the matched-pairs analysis (involving only 11 cases in each group) are at best suggestive on the additional question of a causal link between the emotion self-regulation skills, improvements in HRV, and increased test performance. Even so, the explanatory efficacy of the intervention effect would be strengthened with corroborating evidence of a relationship between student practice of the emotion self-regulation skills and the observed outcomes. While self-report data on this issue were gathered, a full analysis of these data is not yet complete; the findings will be presented in a second article (Bradley et al. 2010), reporting the primary results of the larger study.

Limitations

The study had several limitations. One concerns the lack of baseline equivalence between the intervention and control groups, particularly in terms of ethnic composition and academic level (regular vs. advanced academic classes). While this mirrored differences between the two 10th grade school populations in the larger study (see Bradley et al. 2007), the effort to compensate for these differences, by using a random stratification procedure on these variables to select the two samples for the physiological study, was compromised by unanticipated conflicts between student class schedules and the prearranged times for the experiment. The resulting large difference between the two groups on academic level severely restricted the ability to construct a statistically adequate matched-pairs comparison in which test performance and test anxiety were controlled at baseline measurement. In addition, at a physiological level, students in the intervention group began the study with lower baseline HRV than those in the control group. However, all of these differences could reasonably be expected to work *against* the intervention group, thereby minimizing the observed post-intervention differences between the two groups. Had the two groups begun the experiment on an equivalent academic, ethnic, and physiological platform, it is likely that the pattern of results would have even more strongly favored the intervention group.

Another limitation of the study was the lack of information to specifically identify students for whom English is a second language, who were more numerous in the intervention school. While it is highly likely that this difference in English language proficiency had a notable impact on the CST English-Language Arts test scores, without these data, we were unable to control for the effect of this factor on test performance.

Also, while this study attempted to simulate the stressful conditions of taking a standardized academic test by having students perform the Stroop Test in a controlled environment, the Stroop Test is not an achievement test and, therefore, consideration must be given to how closely it approximates a student's actual experience of taking a high-stakes examination. It is possible that had we been able to measure students' physiological processes prior to taking an actual high-stakes test, we may have found different results. However, given the considerable test-related stress and anxiety that most students report, it is likely that an even stronger relationship between the physiological parameters, socioemotional measures, and test performance would have been found.

Finally, limited resources prevented us from capitalizing on our wait-listed (delayed-intervention) design for the control group. This was unfortunate, as it meant that we were unable to gather data to assess the replication effects of what, effectively, was a second wave of treatment.

Summary and Conclusion

This investigation adopted a broadened approach to studying and addressing the problem of student test anxiety, and, in so doing, has provided new findings regarding the interactions between physiological processes, emotions, learning, and cognitive performance.

Notwithstanding the above limitations, which should be addressed in future research, the data from this study present a pattern of consistent results showing that: (1) students who received the intervention program appear to have learned how to better self-regulate their emotions and intentionally shift into the psychophysiological coherence state under stressful conditions; and (2) the students most in need of help in managing their stress—the high test anxiety/low test-performing subgroup—appear to have internalized the benefits of the program's emotion self-regulation tools, to the extent that they exhibited an emotional profile of significantly reduced negative affect and test anxiety, and a shift to healthier, more coherent baseline pattern of physiological activity. Finally, there is suggestive evidence from the matched-pairs analysis that reduced test anxiety and increased psychophysiological coherence appear to be directly associated with improved test performance.

Starting with the study's methodological implications, the electrophysiological measurements used here contribute to an entirely new window on student cognitive function, emotions, and test anxiety. Not only is this a vista to a new level of analysis—namely, that of the psychophysiological level—but the data collected are *objective*, providing an index of the physiological substratum of stress, test anxiety, and emotional function that is not filtered or distorted by the subjective reality of a student's perceptions (Appelhans and Luecken 2006). On the basis of the rich harvest of findings and potential new understandings offered by HRV data (Thayer et al. 2009), we believe that the inclusion of such physiological measurements in educational research presents a great opportunity for deepening the understanding of the critical relationship between psychophysiological processes, emotions, learning, and academic performance (Immordino-Yang and Damasio 2007). Our results also attest to Segerstrom and Solberg Nes's (2007) point, that HRV measures of self-regulatory strength and effort can, indeed, be successfully investigated outside the laboratory in a controlled field context, such as the school setting in this study—as was also demonstrated in an earlier study of middle school students (McCraty et al. 1999).

In line with other studies on the utility of HRV (Appelhans and Luecken 2006; McCraty et al. 2006; Tiller et al. 1996; Thayer et al. 2009; Segerstrom and Solberg Nes 2007), the HRV measurements used in this study demonstrate that students exposed to the TestEdge program had acquired the self-regulatory ability to shift, under the pressure of a testing situation, into an optimal psychophysiological state conducive to emotional stability, improved cognitive performance, and overall health. This result was associated with a significant reduction in mean test anxiety and negative affect—especially for those in the high test anxiety subgroup, and a marginally significant improvement in standardized test performance for a small matched-pair subsample of students. Perhaps even more notable, the physiological data revealed that the students with high test anxiety had instantiated a healthier, more adaptive *baseline* pattern of psychophysiological function: they exhibited increased HRV and heart rhythm coherence during the experiment even *without* conscious use of the emotion regulation tools. This is likely the result of the brain and body's familiarization with the psychophysiological correlates of the coherence state which had occurred through the learning and use of the coherence-building techniques. When maintained, the expected long-term consequences of this systemic repatterning of psychophysiological activity are sustained improvements in nervous system function, increased stress resiliency, greater emotional stability and control, and improved cognitive performance (McCraty et al. 2006; Thayer et al. 2009).

The fact that such a shift was evident in tenth grade students after a 4-month supplementary classroom program is noteworthy, and has important implications for our approach to education. Given that the program's core intervention utilizes a set of *positive emotion-based* self-regulation techniques that engage the *whole* psychophysiological system, this study's findings challenge many of the most basic assumptions underlying the current educational model, which focuses almost exclusively on cognitive processes (Elias and Arnold 2006; Immordino-Yang and Damasio 2007; Salovey and Sluyter 1997). Moreover, if similar programs were integrated into our educational system even earlier in our children's education and maintained throughout the educational trajectory (e.g., Bradley et al. 2009; McCraty et al. 1999), the accumulated benefits in self-regulatory strength and effort—improved physiological health, socioemotional competence, learning, and academic performance—would be expected to improve student educational experience and achievement, and thus enhance their readiness to assume their adult roles and responsibilities in society (Salovey and Sluyter 1997). Thus, it is our hope that the promising results of this study will help open the door to a new area of scientific inquiry—one concerning how we can best leverage the fundamental interconnections among physiological, emotional, cognitive, and social processes to create optimal educational environments in which all students will flourish.

Acknowledgments This study was funded by the U.S. Department of Education's Fund for the Improvement of Education, grant number U215K040009. We would like to give special mention and acknowledgment to the administrators, teachers, and students at the primary study schools, including the site for the pretests and pilot study. Among these, we express particular appreciation to the following individuals from the intervention school: the Superintendent, Vice-Principal, Senior English Teacher and Project Coordinator, and Head of Technology. At the control school, we thank the Principal, Associate Principal, and key teachers who provided logistical and other support in making the study implementation a success. Also we are especially grateful to the team of highly dedicated and enthusiastic graduate students from Claremont Graduate University's School of Educational Studies, who participated in the fieldwork and data collection in all phases and sub-studies of the TENDS research project. From the HeartMath Research Center, Jackie Waterman deserves special mention for her supportive role in the study. We also express our gratitude to the many teachers who participated in the HeartMath trainings and who made room for the TestEdge program in their classes. Ultimate appreciation goes to all the students who participated in this study. Finally, we thank the journal's Editor-in-Chief for helpful comments on an earlier draft of this article.

Technical Appendix: Derivation of the HRV Measures from the Electrophysiological Data

Continuous pulse plethysmograph recordings (at a sample rate of 250 Hz) were digitized using a model MP30 data acquisition hardware system (Biopac Systems) onto a Dell Latitude laptop computer. These data were then transferred to a PC workstation for RR interval calculation and artifact editing, where all abnormal intervals were eliminated, first, by automated algorithm, followed by manual inspection and correction by an experienced technician. Next, a regularly-spaced HRV time series was derived from the RR intervals by linear interpolation. Gaps in the time series resulting from noise or ectopic beats were filled in with linear splines. The RR interval power spectrum was computed over 3 min of the recording interval for the resting baseline and stress preparation phases of the experiment, beginning 30 s from the initiation of each phase.

Frequency domain measures were calculated by, first, linear de-trending, which is accomplished by subtracting a straight line (standard least-squares method) from the RR interval segment. Then a Hanning window was applied, and the power spectral density (PSD) was computed. The frequency domain measures of RR variability were computed by integration over their frequency intervals. We calculated the power to within two frequency bands of the RR interval power spectrum: (1) low frequency (LF) power (0.04 to <0.15 Hz); and (2) high frequency (HF) power (0.15 to <0.4 Hz). In addition, we calculated total power (power in the band <0.4 Hz) and the coherence ratio. The coherence ratio was calculated as follows: peak power/(total power − peak power), where peak power is a 0.03-Hz-wide area under the largest peak in the 0.04–0.26 Hz region of the HRV power spectrum (Tiller et al. 1996; McCraty et al. 2006).

The time domain HRV measures employed in this study were: the mean heart rate (HR); the mean RR interval; the standard deviation of all normal RR intervals; and the standard deviation of all normal intervals for each segment in the recording. To correct for the skewed distribution of frequency domain and coherence ratio measures, the statistical analysis was performed on the natural log transform values; absolute values are also reported.

Interpreting the HRV Measures

The mathematical translation of HRV into power spectral density measures is accomplished by a Fourier transform function, and is used to discriminate and quantify sympathetic and parasympathetic activity as well as overall autonomic nervous system activity. Power spectral analysis deconstructs the heart rhythm pattern into its constituent frequency components and quantifies the relative power of these components. In a typical analysis, the HRV power spectrum is divided into three main ranges, and each range is associated with an underlying physiological mechanism that gives rise to the oscillations in that range.

The very low frequency (VLF) range (0.0033–0.04 Hz) is primarily an index of sympathetic activity,[10] while power in the high frequency (HF) range (0.15–0.4 Hz), reflects more rapidly occurring changes in the beat-to-beat heart rate, which are primarily due to modulation of the efferent parasympathetic activity associated with changes in respiration. The frequency range encompassing the 0.1 Hz region is called the low frequency (LF) range (0.04–0.15 Hz), and it reflects activity in the feedback loops between the heart and brain that control short-term blood pressure changes and other regulatory processes. The physiological factors contributing to activity in the LF range are complex, reflecting a mixture of sympathetic and parasympathetic efferent and afferent activity as well as vascular system resonance.

Heart rhythm coherence is reflected in the HRV power spectrum as a large increase in power in the low frequency (LF) band (typically around 0.1 Hz) and a decrease in the power in the VLF and HF bands. A coherent heart rhythm can therefore be defined as a relatively harmonic (sine wave-like) signal with a very narrow, high-amplitude peak in the LF region of the HRV power spectrum and no major peaks in the other regions.

References

Appelhans, B. M., & Luecken, L. J. (2006). Heart rate variability as an index of regulated emotional responding. *Review of General Psychology, 10*(3), 229–240.

Arguelles, L., McCraty, R., & Rees, R. A. (2003). The heart in holistic education. *Encounter: Education for Meaning and Social Justice, 16*(3), 13–21.

Armour, J. A., & Ardell, J. L. (Eds.). (1994). *Neurocardiology*. New York: Oxford University Press.

Bradley, R. T., & Atkinson, M. (2004). *Student opinion survey*. Boulder Creek, CA: Institute of HeartMath.

Bradley, R. T., Atkinson, M., Tomasino, D., Rees, R. A., & Galvin, P. (2009). *Facilitating emotional self-regulation in preschool children: Efficacy of the early HeartSmarts program in promoting social, emotional, and cognitive development*. Boulder Creek, CA: HeartMath Research Center, Institute of HeartMath, Publication No. 09-06-01. Available as an electronic monograph at: http://www.heartmath.org/research/scientific-ebooks.html.

Bradley, R. T., McCraty, R., Atkinson, M., Arguelles, L., Rees, R. A., & Tomasino, D. (2007). *Reducing test anxiety and improving test performance in America's schools: Results from the TestEdge national demonstration study*. Boulder Creek, CA: HeartMath Research Center, Institute of HeartMath, Publication No. 07-04-01. Available as an electronic monograph at: http://www.heartmath.org/research/scientific-ebooks.html.

Bradley, R. T., McCraty, R., Atkinson, M., Rees, R. A., & Tomasino, D. (2010, in preparation). Improving emotion self-regulation, test anxiety, and test performance in America's high schools: Results from the TestEdge National Demonstration Study.

Bradley, R. T., Young, W. Y., Ebbs, P., & Martin, J. (1993). Characteristics of advanced-level dietetics practice: A model and empirical results. *Journal of the American Dietetic Association, 93*(2), 196–202.

Cameron, O. G. (2002). *Visceral sensory neuroscience: Interoception*. New York: Oxford University Press.

Childre, D., & Martin, H. (1999). *The HeartMath solution*. San Francisco: HarperSanFrancisco.

Childre, D., & Rozman, D. (2005). *Transforming stress*. Oakland, CA: New Harbinger.

Cizek, G. J., & Burg, S. S. (2006). *Addressing test anxiety in a high-stakes environment: Strategies for classrooms and schools*. Thousand Oaks, CA: Corwin Press.

Damasio, A. (2003). *Looking for Spinoza: Joy, sorrow, and the feeling brain*. Orlando: Harcourt.

---

[10] VLF power was not analyzed in the short-term HRV recordings collected in this study.

Daugherty, A. K. (2006). *Physiological, cognitive, and psychosocial effects of emotional refocusing: A summative and formative analysis*. Doctoral dissertation, Faculty of Education, Claremont Graduate University, Claremont, CA.

Elias, M. J., & Arnold, H. (Eds.). (2006). *The educator's guide to emotional intelligence and academic achievement: Social-emotional learning in the classroom*. Thousand Oaks, CA: Corwin Press.

Erford, B. T., & Moore-Thomas, C. (2004). Testing FAQ: How to answer questions parents frequently ask about testing. In J. E. Wall & G. R. Walz (Eds.), *Measuring up: Assessment issues for teachers, counselors, and administrators* (pp. 535–555). Greensboro, NC: ERIC Clearinghouse on Counseling and Student Services.

Fredrickson, B. L. (2002). Positive emotions. In C. R. Snyder & S. J. Lopez (Eds.), *Handbook of positive psychology* (pp. 120–134). New York: Oxford University Press.

Friedman, B. H. (2009). Feelings and the body: The Jamesian perspective on autonomic specificity of emotion. *Biological psychology*, in press. doi:10.1016/j.biopsycho.2009.10.006.

Friedman, B. H., & Thayer, J. F. (1998a). Anxiety and autonomic flexibility: A cardiovascular approach. *Biological Psychology, 49*(3), 303–323.

Friedman, B. H., & Thayer, J. F. (1998b). Autonomic balance revisited: Panic anxiety and heart rate variability. *Journal of Psychosomatic Research, 44*(1), 133–151.

Greenberg, M. T., Weissberg, R. P., O'Brien, M. U., Zins, J., Fredericks, L., Resnik, H., et al. (2003). Enhancing school-based prevention and youth development through coordinated social, emotional, and academic learning. *American Psychologist, 58*, 466–474.

Hartnett-Edwards, K. (2006). *The social psychology and physiology of reading/language arts*. Doctoral dissertation, Faculty of Education, Claremont Graduate University, Claremont, CA.

Hartnett-Edwards, K. (2008). *Stress matters: The social psychology and physiology of reading/language arts achievement*. Saarbrücken, Germany: Verlag Dr. Müller (VDM).

Hembree, R. (1988). Correlates, causes, effects, and treatment of test anxiety. *Review of Educational Research, 58*(1), 47–77.

Hill, K. T. (1984). Debilitating motivation and testing: A major educational problem, possible solutions, and policy applications. In R. Ames & C. Ames (Eds.), *Research on motivation in education: Student motivation* (pp. 245–274). Orlando, FL: Academic.

Hollingsworth, T. (2007). *Four years into no child left behind: A profile of California tenth grade students' well-being and mixed methods analysis of its associations with academic success*. Doctoral dissertation, Faculty of Education, Claremont Graduate University, Claremont, CA.

Immordino-Yang, M. H., & Damasio, A. (2007). We feel, therefore we learn: The relevance of affective and social neuroscience to education. *Mind, Brain, and Education, 1*(1), 3–10.

Institute of HeartMath. (2004). *TestEdge: Getting in sync for test success*. Boulder Creek, CA: HeartMath LLC.

Isen, A. M. (1999). Positive affect. In T. Dalgleish & M. Power (Eds.), *Handbook of cognition and emotion* (pp. 522–539). New York: Wiley.

James, W. (1884). What is an emotion? *Mind, 9*(34), 188–205.

Lane, R. D., McRae, K., Reiman, E. M., Chen, K., Ahern, G. L., & Thayer, J. (2009). Neural correlates of heart rate variability during emotion. *NeuroImage, 44*, 213–222.

Lazarus, R. S. (1966). *Psychological stress and the coping process*. New York: McGraw Hill.

LeDoux, J. E. (1994). Cognitive-emotional interactions in the brain. In P. Ekman & R. J. Davidson (Eds.), *The nature of emotion: Fundamental questions* (pp. 216–223). New York: Oxford University Press.

LeDoux, J. (1996). *The emotional brain: The mysterious underpinnings of emotional life*. New York: Simon and Schuster.

Luskin, F., Reitz, M., Newell, K., Quinn, T. G., & Haskell, W. (2002). A controlled pilot study of stress management training of elderly patients with congestive heart failure. *Preventive Cardiology, 5*(4), 168–172, 176.

Mayer, J. D., Roberts, R. D., & Barsade, S. G. (2008). Human abilities: Emotional intelligence. *Annual Review of Psychology, 59*, 507–536.

McCraty, R. (2005). Enhancing emotional, social, and academic learning with heart rhythm coherence feedback. *Biofeedback, 33*(4), 130–134.

McCraty, R., Atkinson, M., Lipsenthal, L., & Arguelles, L. (2009). New hope for correctional officers: An innovative program for reducing stress and health risks. *Applied Psychophysiology and Biofeedback, 34*(4), 251–272.

McCraty, R., Atkinson, M., Tiller, W. A., Rein, G., & Watkins, A. D. (1995). The effects of emotions on short-term power spectrum analysis of heart rate variability. *American Journal of Cardiology, 76*(14), 1089–1093.

McCraty, R., Atkinson, M., & Tomasino, D. (2003). Impact of a workplace stress reduction program on blood pressure and emotional health in hypertensive employees. *Journal of Alternative and Complementary Medicine, 9*(3), 355–369.

McCraty, R., Atkinson, M., Tomasino, D., & Bradley, R. T. (2006). The coherent heart: Heart–brain interactions, psychophysiological coherence, and the emergence of system-wide order. Boulder Creek, CA: HeartMath Research Center, Institute of HeartMath, Publication No. 06-022. Available as an electronic monograph at: http://www.heartmath.org/research/scientific-ebooks.html.

McCraty, R., Atkinson, M., Tomasino, D., Goelitz, J., & Mayrovitz, H. N. (1999). The impact of an emotional self-management skills course on psychosocial functioning and autonomic recovery to stress in middle school children. *Integrative Physiological and Behavioral Science, 34*(4), 246–268.

McCraty, R., Barrios-Choplin, B., Rozman, D., Atkinson, M., & Watkins, A. D. (1998). The impact of a new emotional self-management program on stress, emotions, heart rate variability, DHEA and cortisol. *Integrative Physiological and Behavioral Science, 33*(2), 151–170.

McCraty, R., & Childre, D. (2004). The grateful heart: The psychophysiology of appreciation. In R. A. Emmons & M. E. McCullough (Eds.), *The psychology of gratitude* (pp. 230–255). New York: Oxford University Press.

McCraty, R., & Tomasino, D. (2006). Emotional stress, positive emotions, and psychophysiological coherence. In B. B. Arnetz & R. Ekman (Eds.), *Stress in health and disease* (pp. 360–383). Weinheim, Germany: Wiley-VCH.

Mezzacappa, E., Tremblay, R. E., Kindlon, D., Saul, J. P., Arseneault, L., Seguin, J., et al. (1997). Anxiety, antisocial behavior, and heart rate regulation in adolescent males. *Journal of Child Psychology and Psychiatry, 38*(4), 457–469.

Niedenthal, P., & Kitayama, S. (Eds.). (1994). *The heart's eye: Emotional influences in perception and attention*. San Diego: Academic Press.

Pine, D. S., Wasserman, G. A., Miller, L., Coplan, J. D., Bagiella, E., Kovelenku, P., et al. (1998). Heart period variability and psychopathology in urban boys at risk for delinquency. *Psychophysiology, 35*(5), 521–529.

Porges, S. W. (1992a). Autonomic regulation and attention. In H. Hayne & R. Richardson (Eds.), *Attention and information processing in infants and adults* (pp. 201–223). Hillsdale, NJ: Erlbaum.

Porges, S. W. (1992b). Vagal tone: A physiologic marker of stress vulnerability. *Pediatrics, 90*(3 Pt 2), 498–504.

Porges, S. W., Doussard-Roosevelt, J. A., & Maiti, A. K. (1994). Vagal tone and the physiological regulation of emotion. In N. A. Fox (Ed.), *Emotion regulation: Behavioral and biological considerations. Monographs of the Society for Research in Child Development, 59*(2–3), 67–186, 250–283.

Pribram, K. H. (1967). The new neurology and the biology of emotion: A structural approach. *American Psychologist, 22*(10), 830–838.

Pribram, K. H. (1991). *Brain and perception: Holonomy and structure in figural processing*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Pribram, K. H., & Melges, F. T. (1969). Psychophysiological basis of emotion. In P. J. Vinken & G. W. Bruyn (Eds.), *Handbook of clinical neurology* (Vol. 3, pp. 316–341). Amsterdam: North-Holland Publishing Company.

Salovey, P., & Sluyter, D. (Eds.). (1997). *Emotional development and emotional intelligence: Implications for educators*. New York: Basic Books.

Schroeder, L. (2006). What high-stakes testing means for the well-being of students and teachers. Doctoral dissertation, Faculty of Education, Claremont Graduate University, Claremont, CA.

Sears, S. J., & Milburn, J. (1990). School-age stress. In L. E. Arnold (Ed.), *Childhood stress* (pp. 224–226). New York: Wiley.

Segerstrom, S., & Solberg Nes, L. (2007). Heart rate variability reflects self-regulatory strength, effort, and fatigue. *Psychological Science, 18*(3), 275–281.

Spielberger, C. D. (1966). Theory and research on anxiety. In C. D. Spielberger (Ed.), *Anxiety and behavior*. New York: Academic Press.

Spielberger, C. D. (1976). The nature and measurement of anxiety. In C. D. Spielberger & R. Diaz-Guerrero (Eds.), *Cross-cultural research on anxiety*. Washington, DC: Hemisphere/Wiley.

Spielberger, C. D. (1980). *Test anxiety inventory*. Menlo Park, CA: Mind Garden.

Spielberger, C. D., & Vagg, P. R. (1995a). Test anxiety: A transactional process model. In C. D. Spielberger & P. R. Vagg (Eds.), *Test anxiety: Theory, assessment, and treatment*. Washington, DC: Taylor & Francis.

Spielberger, C. D., & Vagg, P. R. (Eds.). (1995b). *Test anxiety: Theory, assessment, and treatment*. Washington, DC: Taylor & Francis.

Suess, P. E., Porges, S. W., & Plude, D. J. (1994). Cardiac vagal tone and sustained attention in school-age children. *Psychophysiology, 31*(1), 17–22.

Thayer, J. F. (2007). What the heart says to the brain (and vice versa) and why we should listen. *Psychological Topics, 16*(2), 241–250.

Thayer, J. F., & Brosschot, J. F. (2005). Psychosomatics and psychopathology: Looking up and down from the brain. *Psychoneuroendocrinology, 30*, 1050–1058.

Thayer, J. F., & Friedman, B. H. (1997). The heart of anxiety: A dynamical systems approach. In A. Vingerhoets (Ed.), *The (non) expression of emotions in health and disease*. Amsterdam: Springer.

Thayer, F. T., Hansen, A. L., Saus-Rose, C., & Johnsen, B. H. (2009). Heart rate variability, prefrontal neural function, and cognitive performance: The neurovisceral integration perspective on self-regulation, adaptation, and health. *Annals of Behavioral Medicine, 37*(2), 141–153.

Thayer, J. F., & Lane, R. D. (2000). A model of neurovisceral integration in emotion regulation and dysregulation. *Journal of Affective Disorders, 61*, 201–216.

Thayer, J. F., & Sternberg, E. M. (2006). Beyond heart rate variability: Vagal regulation of allostatic systems. *Annals of the New York Academy of Sciences, 1088*, 361–372.

Tiller, W. A., McCraty, R., & Atkinson, M. (1996). Cardiac coherence: A new, noninvasive measure of autonomic nervous system order. *Alternative Therapies in Health and Medicine, 2*(1), 52–65.

van der Molen, M. W., Somsen, R. J. M., & Orlebeke, J. F. (1985). The rhythm of the heart beat in information processing. In P. K. Ackles, J. R. Jennings, & M. G. H. Coles (Eds.), *Advances in psychophysiology* (Vol. 1, pp. 1–88). London: JAI Press.

Wigfield, A., & Eccles, J. S. (1989). Test anxiety in elementary and secondary school students. *Educational Psychologist, 24*(2), 159–183.

Zeidner, M. (1998). *Test anxiety: The state of the art*. New York: Plenum Press.

Zins, J. E., Weissberg, R. P., Wang, M. C., & Walberg, H. J. (Eds.). (2004). *Building academic success on social and emotional learning: What does the research say?* New York: Teachers College Press.