Testing the Socio-Autonomic Spiral Model of Social Connection and Health

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Abstract

BETHANY ELLEN KOK: Testing the Socio-Autonomic Spiral Model of Social Connection and Health
(Under the direction of Barbara L. Fredrickson)

Social closeness is inextricably tied to physical and mental health, but the psychophysiological mechanisms that link the two are not well understood. The purpose of this dissertation is to present and test a Socio-Autonomic Spiral Model of Social Closeness and Health: A proposed self-sustaining, heritable psychophysiological system in which activity of the vagus nerve promotes self-regulation and social openness behaviors in safe situations in order to achieve the social bonds necessary for survival in the evolutionary past and health in the present. Social bonds, in turn, lead to greater psychological well-being, which results in greater vagal activity and thus more social affiliative behaviors.

The predictions of the model were tested in two studies. In a longitudinal study, experimentally-induced increases in social closeness predicted increased vagal tone over eight weeks, mediated by increases in positive emotions. Contrary to previous work, vagal tone did not moderate the effectiveness of the social closeness induction. In a laboratory study, vagal tone predicted decreased anxiety when anticipating a social interaction, and this effect was mediated by the tendency to preferentially attend to social

stimuli, an indicator of social openness. Unexpectedly, vagal tone was not associated with self-regulation or emotion regulation.

The vagus may represent an evolved psychobiological system that promotes social affiliation and health, however, many open questions remain. In particular, the relationship between vagal tone and self-regulation is unclear and requires further study. Finally, vagal moderation of social closeness inductions may be dependent on the complexity of the induction; future research can explore the characteristics of opportunities that are enhanced by vagal tone.

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INTRODUCTION

Social closeness is an important contributor to psychological and physical well-being. Whether conceptualized as a fundamental psychological need (Baumeister & Leary, 1995; Deci & Ryan, 2000), a bodily nutrient (Beckes & Coan, 2011), or a critical element in stress and coping (Lakey & Orehek, 2011), there is a general scientific consensus that humans function better, and live longer, when they feel close to others (Holt-Lunstad, Smith, & Layton, 2010). The reverse is also true- physical illness symptoms such as inflammation lead to social withdrawal (Eisenberger, Inagaki, Mashal, & Irwin, 2010) and greater reactivity to negative social cues (Inagaki, Muscatell, Irwin, Cole, & Eisenberger, 2012), suggesting that people are more likely to seek out others when they are in good health.

Despite widespread acceptance that social closeness and health are linked, and repeated calls for further empirical investigation (House, Landis, & Umberson, 1988; Uchino, 2009), the psychophysiological mechanisms that drive these links are not well understood. Given the wide variety of health outcomes empirically linked to social closeness (Holt-Lunstad et al., 2010) and the multi-dimensional nature of social closeness itself, which encompasses subjective perceptions, availability of social support, capacity to provide social support and objective social resources (Cohen, 2004; Uchino, 2009), it is safe to assume that a multiplicity of physiological mechanisms exist, and that these mechanisms influence one another. At present, the inflammation response (Miller, Chen, & Cole, 2009), the oxytocin response (Uvnas-Moberg, 2003) and vagal tone (Porges, 1998) can be considered the most likely candidates. Theoretical and empirical work is ongoing in both the inflammation and social behavior (Eisenberger et al., 2010; Ikeda et al., 2011; Inagaki et al., 2012) and oxytocin and social behavior (Bartz, Zaki, Bolger, & Ochsner, 2011; Holt-Lunstad, Birmingham, & Light, 2008; Kemp et al., 2012) literatures; in contrast, theoretically-driven empirical studies of vagal tone in the context of social closeness are scant.

The purpose of this dissertation is to present and test a theoretical model, the Socio-Autonomic Spiral Model of Social Closeness (SASM), that describes the role of vagal tone as a physiological mechanism that connects social closeness and health in a bi-directional relationship unfolding over time. Vagal tone represents the degree of activation of the vagus nerve while at rest, and is associated with good physical health outcomes (Bibevski & Dunlap, 2011; Thayer & Lane, 2007; Thayer, Loerbroks, & Sternberg, 2011; Thayer & Sternberg, 2010; Weber et al., 2010). I posit that the vagus is part of an evolved, heritable psychophysiological system that promotes social affiliative behavior in safe situations in order to achieve the social bonds necessary for survival in the evolutionary past and health in the present. I further posit that this system is self-reinforcing: Social bonds lead to greater psychological well-being, which results in fewer moments of vagal withdrawal and thus higher vagal tone and more social affiliative behaviors. These mutually-enforcing causal relationships unfold over time in a spiral pattern where change in one element of the spiral, such as social closeness, flows onward to influence to other elements of the spiral, such as vagal tone. In such a spiral, even small, momentary changes can accumulate and compound, ultimately transforming a person's social relationships and consequentially impacting health. The prospective bi-directional relationship subserved by vagal tone may explain part of the strong and consistent relationship between social closeness and health.

Within this bi-directional relationship, I also test potential psychological mechanisms through which vagal tone influences social closeness or social closeness influences vagal tone. In order to promote social closeness, vagal tone must influence affect, cognition or behavior in ways that either encourage the formation and maintenance of social relationships or cause the person to interpret social cues as indicating social closeness. The Neurovisceral Integration Model (Thayer & Lane, 2009) situates the vagus within a neurophysiological system that promotes autonomic balance and self-regulation, while the Polyvagal Theory (Porges, 2011) describes the vagus as an evolved mechanism that promotes openness to social relationships through a variety of affective and attentional strategies including prioritizing social stimuli in attention, making positive affective associations with social partners and sending out social affiliative signals. Both self-regulation and social openness, in turn, are associated with positive social outcomes and building social bonds: Self-regulation facilitates the formation and maintenance of social relationships (Finkel & Campbell, 2001), while social openness creates opportunities to form new relationships (Schindler, Fagundes, & Murdock, 2010). Thus, I posit that self-regulation, openness to social relationships or both will mediate the link from vagal tone to social closeness. In turn, social closeness is proposed to affect vagal tone through changes in daily psychological well-being. Greater well-being promotes healthy stress-response patterns such as faster cardiovascular recovery (Fredrickson & Levenson, 1998; Tugade & Fredrickson, 2004) and greater parasympathetic activation (Boehm & Kubzansky, 2012) that are associated with vagal tone (Thayer & Lane, 2007; Weber et al., 2010).

In sum, the Socio-Autonomic Spiral Model links social closeness and health in part through vagal tone, an indicator of parasympathetic activity associated with self-regulation, social openness, psychological well-being and cardiovascular health. Congruent with the Polyvagal Theory (Porges, 2007) and the Neurovisceral Integration Model (Thayer & Lane, 2009), in SASM vagal tone is hypothesized to promote emotion regulation and social openness, both of which facilitate social closeness and building social bonds. The unique contribution of SASM is to include a reciprocal pathway linking social closeness to vagal tone: Social closeness contributes to day-to-day well-being, and increased well-being promotes greater parasympathetic activation. The inclusion of a reciprocal pathway allows the model to describe how patterns of positive social behavior can be maintained over time, ultimately resulting in higher vagal tone and better health. The full model is shown in Figure 1; The paths correspond to sections within the manuscript.

Social closeness is defined as a belief or perception about a person's embeddedness in a social network or networks (Kok & Fredrickson, in press). In this formulation, social closeness may or may not be related to behaviors from relationship partners or objective social position: What matters is the individual's perception of their relationships with others. In addition, social closeness is not limited to close relationships. Any interaction that reminds someone that they belong can increase social closeness.

Social closeness is critical to health. In a three-year longitudinal sample of older adults ranging in age from 60 to 92, fewer interactions with family and friends predicted an increased likelihood of developing hypertension, cancer, liver disease, diabetes and emphysema, even after controlling for the negative effect of illness on frequency of social interactions (Tomaka, Thompson, & Palacios, 2006). A meta-analysis covering 148 studies and over 300,000 participants found that a lack of social closeness ultimately increases the likelihood of premature death by between 50% and 91%, making social isolation a health risk factor on par with smoking (Holt-Lunstad et al., 2010).

Initial attempts to explain the links between social closeness and health focused on the material benefits and lifestyle changes that might be caused by relationships with others, such as receiving social support when under stress (Gleason, Iida, Shrout, & Bolger, 2008), eating more healthfully (Locher et al., 2005) and getting more exercise (Hawkley, Thisted, & Cacioppo, 2009). These factors alone, however, do not account for all the variance in health explained by social closeness (Holt-Lunstad & Smith, 2012), opening the door to the possibility that social closeness may be directly implicated in physiological functioning.

Vagal Tone Leads to Social Closeness

The vagus nerve, the Xth cranial nerve, is a major component of the peripheral nervous system. It acts as a "brake" on the heart and plays a significant role in regulating cardiovascular reactivity (Berntson et al., 1997; Porges, 1995). When the vagus is active, the heart beats more slowly, while vagal withdrawal is associated with a more rapid heart rate. Through the vagal brake, cardiovascular activity can be "customized" to the situation, with higher heart rate during stress or exertion and slower heart rate when at rest. While cardiovascular reactivity is also influenced by the sympathetic nervous system as well as other physiological actions such as respiration, the vagus nerve is the most rapid and fine-grained regulator of cardiovascular activity, making nearly instantaneous changes in response to shifting social cues within the environment (Porges, 1995).

Vagal tone and social closeness have been linked in a variety of studies. Vagal tone prospectively predicts self-perceived social connectedness (Kok & Fredrickson, 2010), and is correlated with secure attachment within adulthood relationships (Diamond & Hicks, 2005), number of supportive friends (Holt-Lunstad, Uchino, Smith, & Hicks, 2007) and high quality marital relationships (Smith et al., 2011). In a longitudinal study of working adults, social closeness was experimentally manipulated by assigning participants to learn loving-kindness meditation, a mental training practice that focuses on learning to self-generate feelings of warmth and love for self and others, or to a wait-list control. After eight weeks of training, meditators increased significantly in self-reported social closeness relative to participants in the wait-list control. Higher starting vagal tone predicted greater gains in social closeness in response to the intervention (Kok, Coffey, et al., in press). To possess higher vagal tone is to have higher quality, more satisfying friendships and romantic relationships. Potential explanations for these enviable associations include that individuals with higher vagal tone have a greater capacity to control what, when and how emotions are expressed, or that they are more likely to prioritize opportunities for social interaction when they are available.

A. Vagal tone and self-regulation

The Neurovisceral Integration Model describes the vagus as an intermediate regulatory structure that coordinates self- regulation efforts in the brain and body (Thayer & Lane, 2009) via reciprocal linkages to brain areas such as the anterior executive region and the central autonomic network, areas critical for goal directed behavior (Thayer & Brosschot, 2005). Vagal tone is associated with emotional and cognitive regulation. Emotion regulation behaviors associated with vagal tone range widely. Vagal tone predicts control over the expression of negative emotions, such as the ability to up- and down-regulate negative facial expressions at will (Demaree, Pu, Robinson, Schmeichel, & Everhart, 2006; Demaree, Robinson, Everhart, & Schmeichel, 2004; Kettunen, Ravaja, Naatanen, & Keltikangas-Jarvinen, 2000) and to inhibit hostile behavior during relationship conflicts (Gyurak & Ayduk, 2008). High vagal tone also predicts the ability to inhibit attention to unpleasant cues (Park, Van Bavel, Vasey, & Thayer, 2012) and lower startle magnitude when viewing negative pictures (Ruiz-Padial, Sollers, Vila, & Thayer, 2003), suggesting the capacity to re-direct attention even from compelling negative stimuli.

A recent review of the neural correlates of vagal tone in humans and animals found that higher vagal activity was associated with activity of the prefrontal cortex, a brain area implicated in cognitive control (Thayer, Hansen, Saus-Rose, & Johnsen, 2009). Vagal tone is also linked to performance on behavioral indices of cognitive control, including working memory (Hansen, Johnsen, & Thayer, 2003; Staton, El-Sheikh, & Buckhalt, 2009), cognitive efficiency (Staton et al., 2009), directed attention (Suess, Porges, & Plude, 1994) and response inhibition (Johnsen et al., 2003; Mezzacappa, Kindlon, Saul, & Earls, 1998) and task persistence after depletion (Segerstrom & Nes, 2007). In one of the only studies to manipulate vagal tone in adults, sailors from the Royal Norwegian Navy were assigned to eight weeks of aerobic training, which is known to increase vagal tone. After eight weeks, all participants completed two measures of cognitive control, a continuous performance task and a working memory task. Half the sample then continued training, while the other half was deployed in circumstances where they would be unable to train: assignment to training or deployment was not random, but based on whether the sailors had applied for future deployment. After four weeks, both the trained and 'de-trained' groups completed the cognitive control measures again. The 'de-trained' group had declined significantly in vagal tone over the four weeks, while the trained group remained the same. The 'de-trained' group also performed more poorly on the measures of executive function than the group that had continued to train. Unfortunately, the authors did not report whether changes in vagal tone mediated the relationship between group assignment and changes in executive function. Though weakened by the lack of random assignment and failure to directly test mediation, this study provides suggestive evidence that vagal tone supports executive function (Hansen, Johnsen, Sollers, Stenvik, & Thayer, 2004).

B. Self-regulation and social closeness

The ability to control behavior by resisting harmful impulses or taking short-term costs for long-term gains is associated with positive social outcomes in children and adults. Work by Eisenberg and colleagues has found that effortful behavioral control, defined by resistance to cheating on a puzzle-box task and teacher-reported ability to maintain and shift attentional focus, predicts teacher-reported social status and tendency to engage in socially appropriate behavior for students in elementary (Eisenberg et al., 1995; Spinrad et al., 2006) and middle school (Eisenberg et al., 2003). Teacher-reported ego control and attentional focus also predicted increases in gaze aversion, facial expressions of sadness and self-reported sympathetic feelings when elementary-age children viewed a sympathy-inducing video (Gurthrie et al., 1997). Teacher-reported behavioral inhibition in pre-kindergarteners is associated with socially competent behaviors such as cooperativeness and sharing (Rhoades, Greenberg, & Domitrovich, 2009).

In adults, self-regulation is related to inhibiting negative relationship behaviors as well as enacting positive social behaviors. A recent review of the literature (Luchies, Finkel, & Fitzsimons, 2011) found that trait self-regulatory capacity predicted a lower likelihood of intimate partner violence (Finkel, DeWall, Slotter, Oaten, & Foshee, 2009) and infidelity (Pronk, Karremans, & Wigboldus, 2011), as well as greater forgiveness for severe transgressions (Pronk, Karremans, Overbeek, Vermulst, & Wigboldus, 2010), within romantic relationships. In two samples, one of mid-life adults and one of elderly adults, self-reported attentional and emotional control predicted sympathy and perspective-taking (Eisenberg & Okun, 1996; Okun, Shepard, & Eisenberg, 2000). Individuals high in trait self-regulatory capacity, and individuals who had not been depleted, were also more tactful, as measured by their ability to inhibit verbal and facial expressions of disgust when presented with a meal of chicken feet by a Chinese experimenter (von Hippel & Gonsalkorale, 2005). Attempts to regulate self-presentation in order to appear more appealing to others deplete self-regulatory resources, while participants who had been depleted in the laboratory were more likely to use ineffective self-presentation strategies such as talking too much or acting arrogant (Vohs, Baumeister, & Ciarocco, 2005). It appears that successful social interactions and sustained positive relationships benefit from self-regulation.

The ability to control emotions is also related to a wide variety of positive social outcomes in adult samples, including global ratings of social well-being, receiving social support from a parent, and having fewer negative interactions with friends (Lopes, Salovey, & Strauss, 2003). Observer reports also reflect the importance of emotion management skills: In one study, friends reported that participants who scored higher in self-reported emotion management had more positive interactions and greater skills in providing emotional support and resolving conflicts (Lopes et al., 2004). Emotion management may also lead to romantic success: In a two-week daily diary study, college-aged participants high in emotion management reported feeling that interactions with the opposite sex were more positive across a wide range of dimensions (Lopes et al., 2004). In addition, emotion management ability predicted the extent to which participants reported that they had succeeded in their self-presentation goals during these interactions, even though emotion management ability was associated with *higher* self-presentation goals.

People high in vagal tone, therefore, may report feeling more social closeness in part because they are better at relationship-critical skills such as behavioral and emotional regulation.

C. Vagal tone and social openness

Porges has proposed that the vagus influences social behavior, and thus social closeness, by promoting affiliation cues such as eye contact and smiling and creating positive affective associations with social stimuli such as the speech and behavior of other people (Porges, 2007). It is critical to note that these vagus-driven changes in attention and affect would occur only under conditions of safety, as the absence of safety cues initiates vagal withdrawal and potentiates freezing or fight-flight related affect and attitudes (Porges, 2007). The effects of these positive social behaviors would accumulate and compound over time, creating and strengthening social bonds.

Anatomical evidence supports the role of the vagus in regulating social openness. Efferent fibers extend from the vagus to facial muscles, particularly in the eyes, and to the small bones in the middle ear that control auditory frequencies, which would enable a person to express positive social emotions with the face, make eye-contact, and focus hearing on the frequencies of the human voice (Beauchaine, 2001; Heilman et al., 2008). Unfortunately, empirical research on the effects of vagal tone on social openness is scarce and largely focused on socially dysfunctional pathologies such as autism and depression.

Individuals with an autism-spectrum disorder demonstrate social dysfunctions ranging from the inability to speak or make eye contact to coldness, anger and lack of empathy in their interactions with others (American Psychiatric Association, 2000). While much about the underlying causes and physiology of autism is unknown, preliminary work suggests that vagal dysfunction may play a role. Children diagnosed with autism show lower vagal tone (Ming, Julu, Brimacombe, Connor, & Daniels, 2005) relative to age-matched controls. Denver (2004) found that autistic individuals showed deficits in vagal tone, eye contact, and the ability to extract human voice from background noise relative to age-matched controls. I and others have speculated that low vagal activity at baseline may be a diagnostic characteristic of autism-spectrum disorders (Porges, 2003).

Depression, like autism, is characterized in part by decreases in the desire for social closeness (Watson, Clark, & Carey, 1988). Those diagnosed with major depressive disorder show low vagal tone (Rottenberg, Clift, Bolden, & Salomon, 2007), as do women with mild depression (Light, Kothandapani, & Allen, 1998) and women suffering from premenstrual dysphonic disorder (Landen et al., 2004). Stimulation of the vagus, via a pacemaker-like device implanted in the neck, also alleviates depression symptoms. Vagus nerve stimulation (VNS) therapy was approved by the FDA in 2005 for the treatment of depression that is unresponsive to therapy and pharmaceutical treatment (Groves & Brown, 2005). In pilot studies and long-term follow up, VNS therapy performed on patients with treatment-resistant depression resulted in a clinically significant improvement in depression symptoms (50% reduction in scores on the Hamilton Depression Rating, HDR) for 30.5% of the sample after 3 months. After one year of continued VNS treatment, 44.1% of the sample showed clinically significant improvement. After two years of treatment, the average HDR score of participants in the sample had decreased from 36.8 to 20.2, indicating clinically significant lasting improvement in depression symptoms (Howland, 2006; Rado & Janicak, 2007).

While the links between vagal tone and social dysfunctional disorders such as autism and depression are suggestive, it is not clear that vagal tone is involved in social attention processes in healthy individuals. Both autism and depression are characterized by widespread parasympathetic dysregulation (Agelink et al., 2004; Anderson, Colombo, & Unruh, in press). Activity of the vagus in a disordered parasympathetic system may have very different psychological and behavioral effects than a similar level of activation in a non-disordered individual, just as cortisol levels, which typically reflect stress, are suppressed in individuals suffering from Post-Traumatic Stress Disorder (Yehuda, 2002). As of this writing, we are aware of no published empirical work that directly links a behavioral measure of social closeness promotion to vagal tone in a neurotypical sample.

D. Social openness and social outcomes

One way of operationalizing a tendency to pursue social closeness is through assessing a person's social goals. Work by Crocker has investigated the effects of self-esteem goals and compassionate goals on relationship satisfaction and social belonging (Crocker, 2011; Crocker, Olivier, & Nuer, 2009). Self-esteem goals include the desire to present a favorable appearance to others and avoid showing weakness or flaws. Compassionate goals include the desire to support and help others. Across a variety of studies of college students covering time spans from three weeks to the length of a college semester, compassionate goals were associated with favorable social outcomes, including growth in social closeness, social support and trust (Crocker & Canevello, 2008), increased available social support in roommate dyads (Canevello & Crocker, 2010; Crocker & Canevello, 2008), and roommates' reports of liking for the participant (Canevello & Crocker, 2011). In contrast, when participants reported self-esteem goals such as wanting others to recognize their good qualities, social closeness decreased, while anxiety, depression and loneliness increased (Canevello & Crocker, 2011; Crocker & Canevello, 2008).

Compassionate social goals were also associated with perceptions from roommates and friends that the participant was able to accurately identify and respond to their needs in a useful way (Reis, Clark, & Holmes, 2004). Responsive individuals are better able to provide wanted support and to capitalize on their relationship partner's good fortune (Gable, Reis, Impett, & Asher, 2004; Maisel, Gable, & Strachman, 2008). As a result, having a responsive partner is related to higher perceived social support in relationship partners and higher relationship satisfaction for both partners in the future (Gable et al., 2004). To the extent that social openness helps a person to correctly identify another's needs and respond to them in a responsive and satisfying way, it should increase the likelihood of success in social interactions, leading to greater social closeness over time.

In addition to creating opportunities to build future social closeness, social openness may directly increase social closeness when in a neutral or positive social environment. Because social closeness is based on a person's perception of their social environment rather than objective reality, an individual who pays attention to a non-threatening social environment may notice more cues of belongingness and thus feel greater closeness than someone in the same situation who is not attending to the social environment. For example, some treatments for chronic loneliness attempt to increase attention toward social cues in order to modify the individual's perception of themselves as socially isolated (Masi, Chen, Hawkley, & Cacioppo, 2011). A greater awareness of social cues might be harmful in a socially toxic environment; however, if the vagus motivates social attention, then threatening social cues would lead to vagal withdrawal and the social closeness promotion system would no longer be active. In other words, if the vagus is involved in promoting social attention and the parasympathetic system is not dysregulated, vagal withdrawal would de-activate the social engagement system almost immediately upon perceiving a threat. For truly isolated individuals, then, increasing attention to social cues would increase stress. Research on loneliness, however, has found that the perception of social isolation can be only weakly related to actual social context, which suggests that for many people, increased social awareness would lead to decreased loneliness and greater social closeness (Hawkley & Cacioppo, 2010).

From an evolutionary perspective, engagement in affiliative behaviors such sharing a food source and compassionate actions such as empathizing with another may initially appear illogical, as they temporarily reduce the resources available to an individual and do not immediately promote either survival or reproduction. The evidence reviewed above, however, suggests that such actions, though potentially costly in the short-term, are ultimately beneficial. Selective Investment Theory posits that human beings are motivated to invest their resources in others, even when it is costly or stressful in the short term, because in the evolutionary past, those who did so accrued social resources over time that contributed positively to their reproductive success (Brown & Brown, 2006). The vagus may help to increase the likelihood of engaging in these short-term-risky, long-term-good behaviors by increasing the positive salience of the social environment and opportunities for affiliation. To the extent that vagal-supported increases in attention to social information and social openness build advantageous social resources, like bonds, the vagus would have increased the odds of survival in the evolutionary past.

Summary

Vagal tone is prospectively associated with social closeness and theoretically linked to two predictors of social closeness, self-regulation and social openness. Behavioral and neurological studies provide empirical evidence linking vagal tone to emotional and cognitive regulation, while evidence associating vagal tone with social openness is scant. Both self-regulation and social openness, in turn, are associated with positive social outcomes including relationship satisfaction, availability of social support, and favorable evaluations from others. However, there is no empirical work that directly tests whether self-regulation or social openness is the mechanism through which vagal tone influences social perceptions or behavior, and thus social closeness.

Social Closeness Leads to Vagal Tone

As individuals experience greater social closeness, their social environments become more positive and less threatening, and they experience greater psychological well-being on a daily basis (Fredrickson, Cohn, Coffey, Pek, & Finkel, 2008). This may lead to higher vagal tone, as there are fewer moments of threat that necessitate vagal withdrawal and more time is spent with the vagus active in order to down-regulate heart rate. High vagal activity, in turn, predicts lower risk for a wide variety of physical illnesses, suggesting that social closeness may promote health in part by increasing vagal tone.

E. Social closeness and psychological well-being

Social closeness is an integral part of many conceptualizations of mental health: Flourishing includes social well-being (Keyes, 2007), Self-Determination Theory cites relatedness (Deci & Ryan, 2000), and warm and supportive ties to others is named a psychological need (Ryff & Singer, 1996). In the absence of social closeness, adults are more likely to become depressed (Glass, De Leon, Bassuk, & Berkman, 2006), to sleep poorly (Cacioppo et al., 2002; Hawkley, Preacher, & Cacioppo, 2010), and to experience cognitive decline (Seeman, Lusignolo, Albert, & Berkman, 2001).

Interventions that aim to increase psychological well-being often target social closeness. Loving-kindness meditation (LKM) is an emotion-training practice drawn from the Buddhist tradition that is used to increase feelings of warmth and caring for self and others (Salzberg, 1995). Compared to participants in a monitoring, waitlist control group, participants randomly-assigned a 7-week LKM workshop showed steady increases in daily positive emotions, which in turn predicted growth in range of resources, including mindfulness, positive social relations, environmental mastery, and self-reported physical health. These gains in resources were consequential for participants, in that they accounted for improved life satisfaction and reduced depressive symptoms (Fredrickson et al., 2008). Pilot evidence suggests that LKM may also effectively treat the negative symptoms of schizophrenia, which include anhedonia, amotivation, and asociality (D. P. Johnson et al., 2011).

Increases in gratitude are also associated with greater well-being. Relative to participants in an active control group or a "write about your best self" group, participants asked to write a letter expressing gratitude to someone increased significantly in happiness over one month, while participants who kept a daily 'gratitude journal' increased in happiness and decreased in depression throughout the six month monitoring period (Seligman, Steen, Park, & Peterson, 2005). Fostering feelings of social closeness, whether through meditation or reflection, appears to be an effective way of increasing psychological well-being.

F. Psychological well-being and Vagal tone

An accumulation of negative life experiences can result in sustained modifications to the body's stress-response systems. Prospective studies in the developmental literature show that early and sustained exposure to stress can have lasting consequences for the functioning of physiological stress-regulation systems such as the Hypothalamic-Pituitary-Adrenocortical (HPA) axis (Repetti, Taylor, & Seeman, 2002). Research on Post-Traumatic Stress Disorder further shows that even in adults, the stress regulation system can be impacted in a significant and lasting way by traumatic life events (Yehuda, 2002). I posit that an accumulation of positive life experiences can work similarly, promoting healthy stress-response patterns such as faster cardiovascular recovery (Fredrickson & Levenson, 1998) that ultimately result in higher vagal tone.

My own empirical work shows that increases in psychological well-being, as indexed by daily reports of positive emotions, can raise vagal tone. In a study of loving-kindness meditation, participants were assigned to either seven weeks of training supplemented by individual practice or to a wait-list control group. Participants in the meditation group increased in positive emotions relative to both themselves at baseline and to participants in the wait-list control, and these increases in positive emotions predicted increased end-of-study vagal tone (Kok, Coffey, et al., in press). This is the first study to show change in vagal tone as a result of positive behavioral change in neurotypical adults, rather than decreases in vagal tone due to cessation of physical activity (Hansen et al., 2004) or increases in vagal tone due to treatment for depression (Arthur, 2006).

Summary

Social closeness is integral to mental health and well-being, and well-being, in turn, is closely entwined with vagal tone (Oveis et al., 2009). While initial empirical evidence links a social closeness induction to gains in positive emotions, which in turn predict increased vagal tone (Kok, Coffey, et al., in press), these findings are ambiguous. The use of a wait-list control group, combined with the complexity of the meditation practice used to induce social closeness, makes it difficult to know whether changes in social closeness played a causal role in the increased well-being and vagal tone (Kok, Waugh, & Fredrickson, in press). Loving-kindness meditation practice also includes training in body awareness, breathing and relaxation, all of which are also associated with increased parasympathetic activity (Chiesa & Serretti, 2009) and which could plausibly result in higher vagal tone. In order to test the causal role of social closeness, it is necessary to design a follow-up study that incorporates an active control group in order to control for the contextual elements of meditative practice, or to use a different social closeness induction, or ideally, both.

The Current Work

The purpose of this dissertation is to test the twin roles of the vagus nerve as a mechanism that bi-directionally links social closeness to health and health to social closeness.

Two predictions are particularly central:

1) Small, gradual changes in social closeness will over time result in significant changes not only in daily quality of life but also in vagal tone.
2) Vagal tone influences social behavior partially by promoting self-regulation and social openness, which increases the likelihood of positive interaction outcomes.

The next two chapters comprise tests of these predictions. In Chapter Two, a longitudinal social closeness induction is used to observe the effects of changes in social closeness on day-to-day affect and the consequences for vagal tone. In Chapter Three, an "anticipated social interaction" protocol is used to test whether self-regulation and social openness mediate the relationship between vagal tone and affective responses to a challenging upcoming social interaction in a group of neurotypical college students.

Finally, Chapter Four evaluates the results of Chapters Two and Three in the context of the Socio-Autonomic Spiral Model of Social Closeness and Health (SASM). I end with a discussion of the implications of SASM for the study of parasympathetic activity and positive social behavior, broadly conceived.

SOCIAL CLOSENESS INCREASES VAGAL TONE BY INCREASING POSITIVE EMOTIONS[1]

Social closeness plays a significant role in mental and physical health. In a meta-analysis of 148 studies covering over 300,000 participants, individuals who reported satisfactory levels of social closeness had a 50% greater likelihood of survival; to contextualize the significance of this effect, regularly engaging in physical activity is associated with only a 30% greater likelihood of survival (Holt-Lunstad et al., 2010). Other prospective studies show that social closeness also buffers against age-related cognitive decline (Seeman et al., 2001) and depression (Glass et al., 2006). Correlational evidence links social closeness to a wide array of physical health indicators, including blood pressure (Hawkley, Thisted, Masi, & Cacioppo, 2010), heart attack morbidity and mortality (Arthur, 2006), immune function (Cohen, Doyle, Skoner, Rabin, & Gwaltney, 1997) and sleep quality (Hawkley, Preacher, et al., 2010). In a three-year prospective study of older adults ranging in age from 60 to 92, interactions with family and friends predicted a decreased likelihood of developing hypertension, cancer, heart disease and emphysema, even after controlling for the negative effect of illness on frequency of social interactions (Tomaka et al., 2006).

Despite this robust literature, the processes through which social closeness influences physical health are largely unknown (Berkman & Syme, 1979; Cohen & Janicki-Deverts, 2009). In order to explore the causal mechanisms that link social

[1] Chapter is written in the form of a manuscript for publication.

closeness to health, it is necessary to utilize experimental and longitudinal methods that manipulate either social closeness or health and follow changes in potential mechanisms and outcomes over time. Longitudinal methods allow the researcher to track small, subtle changes in emotions, cognitions, behavior or physiological state that may not have apparent effects over a brief time period, while experimental methods are critical to identifying causal mechanisms within the complex systems of psychophysiological processes that manifest social behavior and health.

We propose a Socio-Autonomic Spiral Model of Social Closeness and Health (SASM) that represents the robust association between social closeness and health observed in the literature as the consequence of a reciprocal, mutually-reinforcing link between social closeness and health-relevant physiological states. This reciprocal relationship is driven by positive emotions, which promote physiological down-regulation and recovery from stress (Fredrickson & Levenson, 1998), and vagal tone, a physiological measure of autonomic regulation which is associated with positive social behaviors and physical and mental health (Porges, 2007). Social closeness and positive emotions, in turn, are closely tied together, with changes in one causing changes in the other (Berry & Hansen, 1996; Lyubomirsky & Della Porta, 2010; Nelson, 2009). Over time, repeated positive emotional experiences generated by social closeness lead to health-relevant physiological changes including increases in parasympathetic activity as indexed by vagal tone (Kok, Coffey, et al., in press; Kok & Fredrickson, 2010). In turn, anatomical evidence suggests that increases in vagal tone will lead to more social engagement behaviors, such as social eye contact, attention to others and facial expressivity (Porges, 2011) . The relationship between social closeness and health takes the form of a self-reinforcing spiral, in which changes in one area, such as health, reverberate through the spiral across time, leading to congruent changes in vagal tone, social closeness and positive emotions. In this spiral, very small changes in social closeness can result, over time, in significant differences in mental and physical health, with long-lasting consequences for the individual.

Social closeness and positive emotions are closely and reciprocally linked in daily life (Kok & Fredrickson, 2010; Waugh & Fredrickson, 2006). During an average day, people report feeling more positive emotions when interacting with others (Catalino & Fredrickson, 2011; Fredrickson et al., 2008; Srivastava, Angelo, & Vallereux, 2008) than when they are alone. Reflecting on positive social relationships by writing a letter expressing gratitude to someone increases happiness (Seligman et al., 2005), as do induced social interactions with a stranger in a laboratory setting (Berry & Hansen, 1996; Mcintyre, Watson, Clark, & Cross, 1991).

In turn, positive emotions are associated with a parasympathetic functioning, including vagal tone (Kok & Fredrickson, 2010; Oveis et al., 2009). Experimentally induced positive emotions accelerate cardiovascular recovery from stress (Brummett, Boyle, Kuhn, Siegler, & Williams, 2009; Fredrickson & Levenson, 1998; Tugade & Fredrickson, 2004), an index of parasympathetic activity. Ambulatory monitoring studies link positive emotions to other indices of parasympathetic activity including lower heart rate (Steptoe & Wardle, 2005; Steptoe, Wardle, & Marmot, 2005) and decreased cardiovascular reactivity to stress (Ong & Allaire, 2005)

Parasympathetic activity is regulated, in part, by the vagus nerve, a spinal nerve that plays a central role in down-regulating physiological activation, particularly as it pertains to cardiovascular activity, acting as a "brake" to slow down the heart rate in response to environmental safety cues (Porges, 2007). Vagal tone is linked to multiple measures of cardiovascular (Bibevski & Dunlap, 2011) and immune health (Sloan et al., 2007; Thayer & Sternberg, 2006). In a review of the literature, vagal tone was found to predict morbidity and mortality from cardiovascular disease independent of traditional risk factors, and changes in vagal tone were associated with downstream changes in the profile of risk factors for cardiovascular disease (Thayer & Lane, 2007), suggesting that the vagus may play an active role in maintaining physical health.

The vagus is also involved in social behavior, as it coordinates communication between the brain and muscles involved in social communication, including tuning the ear to the frequency of the human voice and directing eye gaze (Beauchaine, 2001; Heilman et al., 2008), and is associated with emotion regulation, particularly facial expressions of emotion (Demaree et al., 2006; Demaree et al., 2004; Kettunen et al., 2000). Higher levels of resting vagal activity are positively associated with many measures of social closeness, including secure attachment (Diamond & Hicks, 2005), self-reported social connectedness (Kok & Fredrickson, 2010) and number of supportive friends (Holt-Lunstad et al., 2007).

In sum, we describe in SASM that social closeness and health may be linked in a spiral relationship where changes in social closeness result in changes in positive emotions. Increases in positive emotions result in greater activity of the parasympathetic nervous system, of which the vagus is a part. Over time, repeated moments of positive emotion and the attendant parasympathetic activity lead to higher resting parasympathetic activity and thus, higher vagal tone. In turn, greater vagal activity leads to greater activation of physiological systems that subserve positive social behavior, leading to increases in social closeness.

In an initial test of SASM, mid-life adults provided a measure of vagal tone and daily reports of emotion and social closeness for nine weeks, ending with a second measure of vagal tone (Kok & Fredrickson, 2010). Starting vagal tone prospectively predicted changes in social closeness and positive emotions, such that participants with higher levels of vagal tone showed greater gains in both variables over the course of the study. In addition, change in social closeness and positive emotions predicted end-of-study vagal tone, controlling for vagal tone at start of study. Across nine weeks, vagal tone both predicted increases in social closeness and positive emotions and was predicted by these same increases, evidence for a naturally-occurring spiral pattern linking social closeness, positive emotions and health through the accumulation of small changes over time.

Experimental evidence for SASM comes from research on an emotion-training intervention known as loving-kindness meditation (LKM). LKM is a Buddhist meditative practice used to increase feelings of warmth and caring for self and others (Salzberg, 1995) is part of a larger family of "heart-focused" practices that also includes compassion meditation (Kok, Waugh, et al., in press). In LKM, individuals are first asked to focus on their heart region and contemplate a person for whom they already feel warm and tender feelings (e.g., their child, a close loved one). They are then asked to extend these warm feelings first to themselves and then to an ever-widening circle of others.

Loving-kindness meditation appears to be an effective way of increasing social closeness in the laboratory and the field. In a laboratory study, participants who engaged in seven minutes of stranger-focused LKM increased in implicit and explicit feelings of closeness to the stranger, while participants in a closely-matched visualization control condition showed a smaller increase in explicitly-reported closeness but no change in implicit ratings (Hutcherson, Seppala, & Gross, 2008). In a longitudinal study of LKM, working adults assigned to learn LKM or to a monitoring wait-list control condition provided daily reports of their emotions and feelings of social connectedness. Meditators attended weekly hour-long group meditation workshops led by a practitioner experienced in teaching LKM and were encouraged to practice independently throughout the week. Participants in the meditation condition showed significant increases in both positive emotions and self-reported social closeness over the nine weeks of the study (Kok, Coffey, et al., in press).

In addition to increasing social closeness, “heart-based” practices such as LKM are associated with improvements in psychological and physical health that correspond to many of the health outcomes associated with social closeness. Compared to participants in a monitoring, waitlist control group, participants randomly-assigned to learn LKM over a 7-week workshop showed steady increases in daily positive emotions, which in turn predicted growth in range of resources, including mindfulness, positive social relations, environmental mastery, and self-reported physical health. These gains in resources were consequential for participants, in that they accounted for improved life satisfaction and reduced depressive symptoms (Fredrickson et al., 2008). Compassion meditation may benefit physical health by reducing affective and physiological reactivity to social stress. The Trier Social Stress Test (TSST) is a well-known method of inducing social-evaluative threat. In a six-week study of compassion meditation, time spent in compassion meditation predicted decreased inflammatory response to the TSST, as indexed by the inflammatory hormone interleukin-6, as well as decreased self-reported distress (Pace et al., 2009).

At least some of the mental and physical health benefits of LKM may be due to meditation-driven increases in social closeness and vagal tone. Unfortunately, few longitudinal studies of LKM have explored underlying mechanisms (but see Fredrickson, et al., 2008; Kok, Coffey, et al., in press), and only one study has directly measured changes in social closeness as a potential mediator of health-related changes brought about by LKM. In this study, participants were assigned to a 7-week meditation workshop or to a monitoring wait-list control, and provided daily reports of social connectedness, measured using items from the UCLA Loneliness scale (Russell, 1996), and a 20-item measure of discrete emotions (Fredrickson, Tugade, Waugh, & Larkin, 2003). Vagal tone was measured before assignment to conditions and after the conclusion of the meditation workshops. In addition to the LKM-driven increases in social closeness mentioned earlier, participants in the meditation condition increased in positive emotions and vagal tone over the course of the study. Further modeling revealed that LKM drove changes in positive emotions, which led to changes in social closeness, which in turn led to higher vagal tone (Kok, Coffey, et al., in press).

Finally, participants' starting level of vagal tone moderated the effectiveness of LKM (Kok, Coffey, et al., in press). SASM predicts that changes in social closeness and vagal tone are interdependent, and thus higher vagal tone should increase responsiveness to a social closeness intervention such as LKM. Supporting this prediction, participants who began the study with higher vagal tone showed a greater rate of increase in positive emotions and social closeness over time in response to LKM (Kok, Coffey, et al., in press).

In Kok et al., social closeness mediated the relationship between changes in positive emotions generated by meditation practice and change in vagal tone, suggesting that social closeness may be a mechanism of action for LKM. Mediation, however, is insufficient evidence to declare that social closeness plays a causal role in the psychophysiological changes associated with LKM (Ospina et al., 2008). Social closeness and positive emotions may, instead, be correlates of some other psychological construct that accounts for the connection between LKM and improved vagal tone; it is also possible that, in this instance, social closeness acts as a mediator because it is correlated with both positive emotions and vagal tone, and thus changes in these two variables will appear to be mediated by social closeness.

The purpose of this study is to test whether experimentally manipulated social closeness plays a causal role in building health through changes in positive emotions and autonomic regulation as measured by vagal tone. This is in contrast to the model tested in Kok, Coffey, et al., which showed that experimentally manipulated positive emotions play a causal role in building health through changes in social closeness (in press). Given the strong reciprocal relationship between social closeness and positive emotions, it is critical to test the causal role of both positive emotions and social closeness using separate manipulations in order to understand their roles in health.

In addition, we test whether social closeness, a mediator of the effect of LKM on vagal tone (Kok, Coffey, et al., in press), is also a causal mechanism of action for LKM. Social closeness was manipulated via daily questions designed to prime positive social attention. Each day for eight weeks, participants randomly assigned to the social closeness condition received a daily email containing the priming questions and an emotions questionnaire. Participants assigned to the control condition received a daily email with neutral questions, as well as the emotions questionnaire. Vagal tone was measured at the beginning and end of the study for all participants. We hypothesize that:

I. Participants in the social closeness condition will increase in positive emotions, relative to participants in the control condition.

II. Vagal tone will moderate the effect of the social closeness manipulation, with higher vagal tone predicting greater gains in positive emotions.

III. Change in positive emotions, in turn, will predict changes in vagal tone.

Figure 2.1 provides a visual representation of the hypotheses.

Pilot test of social connectedness manipulation and placebo control

Before beginning the larger study, we tested the efficacy of the social connectedness manipulation and the control condition in a month-long online pilot test, tracking change in self-reported positive and negative emotions.

Participants

Participants (N=67) were recruited via a university listserv advertisement for a month-long pilot test of an online “stress reduction” study. The resulting sample was 85% Caucasian, 85% female and 43.3% married, with a mean age of 35.7 and ages ranging from 18 to 62.

Social Closeness Manipulation

In Kok & Fredrickson (2010), participants increased in social closeness and positive emotions over nine weeks independent of any experimental manipulation. As long-lasting changes in positive emotions are unlikely in the absence of an external influence (Diener, Lucas, & Scollon, 2006), we speculated that one of the questionnaires in the study might have had a psychoactive effect, and repeatedly completing the questionnaire was causing positive emotions to increase. The emotions questionnaire had been employed in other studies without creating a main effect of time, suggesting that the social closeness questions might have caused the changes in positive affect and social closeness observed in that study.

In order to manipulate social closeness, therefore, we assigned participants in the experimental condition to receive each day via email the same social closeness items that were used in Kok and Fredrickson (2010). Participants were asked to list the three social interactions in which they spent the most time that day. They then rated these three interactions in aggregate using 2 items adapted from Russell’s UCLA Loneliness scale (1996): “During the social interactions, I felt “in tune” with the person/s around me” and

“During the social interactions, I felt close to the person/s,” using a 7-point scale (1= *not at all true*, 7=*very true*).

The placebo control condition was designed to match the social closeness condition by inducing participants to look back over their day to select particular episodes and to make a value judgment about those episodes using criteria provided by the experimenters. Participants were asked to list the three tasks in which they spent the most time that day. They then rated those three tasks in aggregate on 2 items: “During the tasks, I felt the tasks were useful for me” and “During the tasks, I felt the tasks were important for me” using a 7-point scale (1= *not at all true*, 7=*very true*).

Daily emotion reports

The modified Differential Emotions Scale was used for participants’ daily emotion reports (Fredrickson, in press). Participants rated their strongest experiences of 20 emotions in the past day on a 5-point scale (0 = *not at all* to 4 = *extremely*). Participants’ mean positive emotion score was composed of amusement, awe, gratitude, hope, inspiration, interest, joy, love, pride and serenity (α = .92). Participants’ mean negative emotion score was composed of anger, boredom, contempt, disgust, embarrassment, fear, guilt, hate, sadness and shame (α =.88).

Procedure

Participants were randomly assigned to the social closeness or control conditions. Each day for four weeks, they received an email containing the experimental or control questions and an emotions questionnaire. At the end of the four week period, participants completed a demographics questionnaire and were thanked and debriefed.

Results and Discussion

Data were analyzed using separate multilevel models for positive and negative emotions. Each model includes linear and quadratic time effects, experimental condition and the interactions between the time predictors and condition, in order to explore the linear and non-linear effects of the experimental condition on positive emotions over time. The models also control for the effects of weekends and allow the intercept, linear slope of time, quadratic slope of time and weekend estimates to vary randomly between participants.

Results are shown in Table 2.1. Participants in the social closeness condition showed a significant linear increase in positive emotions over time ($\beta = .03$, $p = .05$) relative to participants in the control condition. There were no differences by condition in the negative emotions model. In both models, participants showed a linear drop in emotion intensity over the course of the study, independent of condition. This pattern was unanticipated. In the positive emotions model, it may be attributed to anticipating the end of summer, as the sample was composed entirely of university students, employees and professors and data collection started in mid-July and ended in mid-August at the start of the fall semester. It is unclear why participants would show decreases in negative emotion intensity as well.

The results of the pilot study suggest that the social closeness manipulation is effective in increasing positive emotions over the course of a month, relative to the placebo control condition.

Main Study

Participants

Due to an error in data collection, demographic data was only gathered at the end of the study and thus only represents participants who completed the end-of-study survey. Of the participants who completed the demographics measures, 80.5% were female, 61% were currently married, 85.4% self-identified as Caucasian and 89.6% had completed a bachelor's degree or more. Mean age was 47.6, ranging from 27 to 62.

Social closeness manipulation

Same as in pilot study.

Vagal tone

Vagal tone was measured via respiratory sinus arrhythmia (RSA), a non-invasive measure of cardiac vagal control characterized by increases in heart rate with inspiration and decreases in heart rate with expiration (Berntson et al., 1997). Continuous recordings were made of heart rate and respiration measures at a sampling rate of 1000 Hz. From these recordings, second-by-second averages were computed. Disposable snap electrodes were placed in a bipolar configuration on lateral sides of the chest on the lowermost ribs to measure the participant's echocardiogram (ECG). Respiration was collected with pneumatic bellows, placed around the participant's chest at the bottom of the sternum. All data were inspected offline and corrected for artifacts. RSA was calculated off-line based on changes in heart rate associated with respiration using a modified Grossman peak-to-valley method (Grossman, 1983) with re-sampling every 125 ms. Data was excluded if a peak could not be identified. The influence of respiration on RSA was removed by regressing RSA on respiration over the same period and extracting the residualized RSA values, free of variability due to respiration.[2]

Daily emotion reports

The modified Differential Emotions Scale was again used for participants' daily emotion reports, with positive emotion (α = .92) and negative emotion (α = .81) subscores.

Procedure

Participants were recruited from a local company for a study to "test a new method to reduce stress." Advertisements were sent via internal email and approved by company leadership, as well as through an informational talk given several weeks prior to commencing the study. In both formats, participants were given a description of the study and had the opportunity to sign up online for an initial testing session with an experimenter on the company grounds. Information about the participants' identities was not released to the company. Upon arriving at the testing session, participants were given more information about the study and had the choice to give their consent.

After consenting, participants provided a four-minute free-respiration vagal tone baseline while alone in a small, quiet room. After completing the initial meeting, participants began receiving the daily emails. For the first week, participants received only questions regarding their emotions, in order to establish a baseline. After one week, participants were randomly assigned to condition and began receiving the condition

[2] Three participants' RSA scores from time 1 and seven were excluded from time 2 due to high ECG impedances. RSA data from one participant was excluded due to RSA values that appeared anomalous in combination: A value approximately 2 standard deviations below the mean at time 1 and approximately 4 standard deviations above the mean at time 2.

instructions in their daily email along with the emotions questionnaire. Participants completed the daily online measures for a total of 56 days; 7 days of baseline and 49 days of experimental or control instructions. At the end of the 56-day period, participants were asked to schedule a time for a final physiological data collection session and debriefing on the company grounds. Approximately one month later, participants received their compensation via email in the form of a password-protected in-depth report summarizing their individual responses to the intervention, compared to the group mean.

Data Analysis

Attrition. Seventy-seven participants enrolled in the study and completed the initial vagal tone measure. Forty-two participants continued in the study until the end and completed the final vagal tone and demographics measure. Participants who completed the study reported significantly less positive emotion during the baseline week than participants who did not complete (t= -2.23, $p < .05$), but did not differ reports of negative emotions ($t = 1.18$, $p = .24$) or starting vagal tone ($t = -1.24$, $p = .22$). Participants in either condition were also equally likely to leave the study early (t=.902, $p = .37$).

The high rate of attrition may be attributable in part to the subtlety and day-to-day sameness of the experimental intervention. At debriefing, some participants who had not dropped out reported frustration or boredom with the study, and 88% said they thought they were in the control condition. This belief was independent of the participant's actual condition assignment ($\chi^2(1, 41)= .317$, $p = .57$). Given these evaluations, it is possible that the participants who stayed with the study did so because they were in greater distress than those who quit, and their distress motivated them to persist in the study even when it seemed tedious or ineffectual.

Hypothesis I: Participants in the social closeness condition will experience an increase in positive emotions, relative to participants in the waitlist control condition. There will be no effect for negative emotions. Hierarchical linear modeling was used to analyze the effect of condition on change in positive emotions over time. Participants' daily emotion reports were concatenated into week-by-week averages in order to correspond to the SEM used to test Hypothesis II, as the small sample size meant there was insufficient power for a day-by-day SEM. The model included time, condition and the interaction of time and condition as predictors, as well as random intercepts and a random effect for time, in order to account for individual differences in participants' starting levels of positive emotions and rate of change in positive emotions over the course of the study. Because the data were aggregated at the week level, it was not possible to include a predictor for weekend as was done in the pilot study. The interaction of condition and time was significant and positive ($\beta = .027$, $p < .05$), suggesting that the social closeness manipulation increased participants' experiences of positive emotions over the course of the study. There was no direct effect for condition ($\beta = .020$, $p = .91$). A model with the same predictors and error structure was fitted for negative emotions, but the interaction of condition and time was not significant ($B = .018$, $p = .15$), nor was there a direct effect for condition ($B = -.036$, $p = .66$).

Hypotheses II and III: Vagal tone will moderate the effect of the social closeness manipulation on positive emotions, while increases in positive emotions will cause an increase in end-of-study vagal tone. In order to simultaneously test the effect of vagal tone on change in positive emotions and the effect of positive emotions on change in vagal tone, a latent growth curve model was fitted to the data using Mplus (Muthen & Muthen, 1998-2012). Condition, starting vagal tone and their interaction predicted both the latent positive emotions intercept and the latent positive emotions slope. Consistent with the recommendations given in Curran & Hussong (2003), week-by-week positive emotions scores were constrained to one on the latent intercept term, while loadings for the slope term were as follows: 0 for the baseline week, 1 for week 1, 2 for week 2, etc. The residual of each weekly positive emotions variable was allowed to covary with the residual of the positive emotions of the following week; these covariances were constrained to be equal, with no significant decrement in model fit relative to a model in which the week-by-week residual covariances were freely estimated. Because previous work has shown an association between vagal tone and positive affect (Oveis et al., 2009), starting vagal tone was also allowed to covary with the week 1 positive emotions score. Finally, both the positive emotions intercept and slope were used to predict end-of-study vagal tone, controlling for starting vagal tone.

The model is shown in Figure 2.2, with path coefficients and significance tests in Table 2.2. Model fit was within the range commonly seen in latent growth models(Widaman & Thompson, 2003), with an RMSEA of .082 and CFI/TFI scores of .945 and .938. Contrary to our second hypothesis, the path representing the interaction of t1 vagal tone and condition on positive emotion slope (path d) was not significant (b = -.10, p = .69) suggesting that the social closeness intervention was equally effective for all participants in the experimental condition, regardless of starting vagal tone. The path representing the direct effect of experimental condition on change in positive emotions was significant and positive (path b; $b = .38$, $p < .05$), corresponding to the results of the hierarchical linear model above. The critical path representing hypothesis III (path h) was significant and positive ($b = .65$, $p = .01$), suggesting that increased positive emotions resulted in increased vagal tone. A second model was fitted that included a direct path from experimental condition to residualized end-of-study vagal tone; this path was not significant ($p = .40$), while all other paths remained significant, suggesting that the effect of the intervention on vagal tone was mediated by change in positive emotions.

We attempted to fit a model with the same structure and paths for negative emotions, however, minimal variance in negative emotion scores over time meant that the model did not converge, nor did similar models with small variations in structure.

Discussion

Social closeness appears to play a causal role in generating positive affect and health-related physiological states. Consistent with our previous work (Kok, Coffey, et al., in press), experimentally manipulating social closeness set off a cascade of psychophysiological changes, beginning with increased daily positive affect, which in turn led to greater autonomic regulation by end of study. Consistent with the Socio-Autonomic Spiral Model of Social Closeness and Health (SASM) proposed here, the robust association between social closeness and health, here represented by vagal tone, was driven by small, incremental changes in psychological state that culminated in detectable physiological change.

Contrary to the predictions of SASM and our previous findings (Kok, Coffey, et al., in press), starting level of vagal tone did not moderate the effect of the social closeness manipulation. In the absence of vagal moderation, the relationship between social closeness and health in this study lacks the bi-directional and reciprocal causality that is critical to a spiral. Social closeness may increase positive emotions and vagal tone, but higher vagal tone did not appear to increase the positive emotion yield of future social closeness opportunities. It is possible that vagal tone did not moderate the effect of the social closeness intervention because the intervention was subtle and required little effort, in contrast to the time commitment and behavioral changes required by loving-kindness meditation. Self-regulation and social attention, the proposed down-stream consequences of vagal tone (Agelink et al., 2004; Porges, 2011; Thayer & Lane, 2009), could plausibly facilitate gains from LKM, but would not be needed to benefit from an intervention that consists of answering two multiple choice questions each day via email.

One purpose of this study was to test the predictions of SASM that social closeness and health are related through a reciprocal, mutually-reinforcing link between social closeness and vagal tone that is driven by changes in positive emotions. We used a longitudinal experimental design to manipulate social closeness in healthy subjects and observed that participants in the experimental condition increased in positive emotions, which in turn increased vagal tone. These findings suggest that social closeness is related to health in part because perceived social closeness leads to more frequent positive emotional experiences. Positive emotions, in turn, activate the parasympathetic nervous system, speeding recovery from negative events and reducing physiological wear-and-tear in ways that increase health and extend the lifespan (Chida & Steptoe, 2008).

A second goal was to test social closeness as a causal mechanism of action in loving-kindness meditation. In a previous study, we showed that LKM increased positive emotions, which increased social closeness, which resulted in higher vagal tone (Kok, Coffey, et al., in press). In that study, social closeness mediated the relationship between positive emotions induced by LKM and vagal tone, but because social closeness was not directly manipulated, we were unable to determine whether social closeness played a causal role in bringing about change in vagal tone. Here, we have shown that experimentally manipulated social closeness does, in fact, increase vagal tone. In combination with our previous study, this is the first empirical evidence that LKM works by changing practitioners' feelings of social closeness, with consequences for health.

In a recent review of the literature, loneliness, or self-perceived social isolation, was associated with a host of psychophysiological dysfunctions including increased risk of cardiovascular disease, depression, and premature death (Hawkley & Cacioppo, 2010), while interventions to treat loneliness improve mental and physical health (Masi et al., 2011). Yet what about people who are not lonely? Our work suggests that increasing social closeness can be beneficial even for people who do not report deficits in their current social lives. Social closeness, then, is more than the absence of loneliness.

This study used repeated measures of self-reported positive emotions in order to understand how changes in subjective day-to-day experiences can be consequential for health. Longitudinal, repeated-measures designs are an excellent way of achieving a fine-grained picture of change over time, but the gain in scope is accompanied by a loss of detail, including the absence of behavioral data. Yet unknown is how increasing social closeness results in more positive emotions: did daily reflections on social closeness inspire participants to have more social interactions, or do they experience their existing interactions more positively, or both? A more detailed investigation of how social behavior and social perceptions change during a social closeness intervention would help to address these questions. Similarly, we do not yet know how changes in positive emotions lead to changes in vagal tone. Previous work suggests that positive emotions dampen physiological responses to stress (Tugade & Fredrickson, 2004), potentially by increasing parasympathetic activity. A great deal of daily experience, however, is not stressful (Oishi, Diener, Napa Scollon, & Biswas-Diener, 2004), and it is not known whether or how positive emotions might also influence parasympathetic activity during those times. Future studies should employ more frequent measures of vagal tone in order to observe how daily events affect parasympathetic activity.

Conclusions

Feeling close to others may be beneficial for health in part because gains in social closeness increase the "daily diet" of positive emotions, which results in higher vagal tone. Vagal tone is an indicator of autonomic flexibility, meaning that people who experience frequent positive emotions may more rapidly adjust their physiological state to match the demands of the moment. This rapid and flexible responsiveness is known to decrease wear-and-tear on the heart (Thayer & Lane, 2007), thus increasing the likelihood of a long and healthy life.

PSYCHOLOGICAL MEDIATORS OF VAGAL EFFECTS ON SOCIAL CLOSENESS

Having evidence that social closeness increases vagal tone, the purpose of this chapter is to test whether vagal tone promotes behaviors that encourage social closeness, and if so, through what mechanisms. Social closeness promoting behaviors will be assessed in the context of an anticipated social interaction paradigm. Because American culture encourages social approach behavior in general (Riesman, Glazer, & Denney, 2001), participants were assigned to either an “easy” or a “difficult” social interaction condition. I hypothesized that vagal tone would predict social closeness promoting behavior in the difficult condition. The difficulty of the social interaction was operationalized by varying the race of the anticipated interaction partner to be either the same or different than the race of the participant. In order to increase the salience of race, participants were told their interaction with their partner would be a conversation about “racial issues.”

The race-based manipulation of interaction difficulty was chosen because of the literature describing interracial interactions as requiring costly self-regulation and eliciting social avoidance (Richeson & Shelton, 2007; Richeson & Trawalter, 2005; Trawalter, Richeson, & Shelton, 2009). Self-regulation is central to some explanations of behavior during interracial contacts (Richeson & Shelton, 2007), as interracial interactions are stressful and deplete self-regulatory resources, particularly for individuals who are motivated to avoid appearing prejudiced (Trawalter, Adam, Chase-Lansdale, & Richeson, 2010; Trawalter & Richeson, 2006). Unfortunately, motivation to avoid appearing prejudiced may backfire as individuals who have been depleted are less able to prevent stereotypical thoughts from resulting in prejudiced behavior (Muraven, 2008), which can lead to avoiding interracial interactions altogether as a way of preventing depletion and coping with stress (Trawalter et al., 2009). Individuals with high vagal tone may be more likely to engage in closeness-promoting behaviors even during difficult, interracial interactions due to their greater social openness and self-regulatory capacity.

Formal Statement of Hypotheses

I. Vagal tone is positively correlated with self-regulation and social openness.

II. Vagal tone, self-regulation and social openness are positively correlated with closeness-promoting behaviors in the difficult interaction condition.

III. The relationship between vagal tone and closeness-promotion in the difficult interaction condition is mediated by self-regulation and social openness.

Method

Participants

Seventy-six college-aged participants (62.9% female) signed up for a study on "Communication and Emotion." The racial breakdown was as follows: 72.9% white and

20% black, with the remaining 7.1% split between Hispanic, Asian, not reported, and one who self-identified as "Mixed."

Measures

Vagal tone. Vagal tone was measured via respiratory sinus arrhythmia (RSA), a non-invasive measure of cardiac vagal control characterized by increases in heart rate with inspiration and decreases in heart rate with expiration (Berntson et al., 1997). Continuous recordings were made of heart rate and respiration measures at a sampling rate of 1000 Hz. From these recordings, second-by-second averages were computed. Disposable snap electrodes were placed in a bipolar configuration on lateral sides of the chest on the lowermost ribs to measure the participant's echocardiogram (ECG). Respiration was collected with pneumatic bellows, placed around the participant's chest at the bottom of the sternum. All data were inspected offline and corrected for artifacts. RSA was calculated off-line based on changes in heart rate associated with respiration using a modified Grossman peak-to-valley method (Grossman, 1983) with re-sampling every 125 ms. Data were excluded if a peak could not be identified. The influence of respiration on RSA was removed by regressing RSA on respiration over the same period and extracting the residualized RSA values.

Social openness. The Polyvagal Theory (Porges, 2003) predicts that vagal tone promotes social attention as part of social openness, and vagal tone is linked to social gaze avoidance in individuals with autism-spectrum disorder (Bal et al., 2010). Based on that knowledge, openness to social interactions was operationalized via a dot-probe task that assessed attention to affectively matched social vs. non-social images.

Image selection. Images were drawn from the International Affective Picture System and the Georgia Face Image Database (Center for the Study of Emotion and Attention—National Institute of Mental Health, 1999; Georgia Institute of Technology, 2007). Social and non-social images were pre-tested online with a group of college students (N=45, 51% female, M age=21.4) to ensure that the categories were similar in valence but different in degree of sociality. In total, 200 images were rated, with each participant rating a randomly-chosen and randomly-ordered sample of 50 of the images to minimize participant fatigue. Each image therefore received an average of eleven ratings of sociality and valence.

Sociality was measured via the following items: "How social is this image?" "How friendly is this image?" "How unfriendly is this image?" (reverse-scored) and "How much does this image make you want to socialize?" Valence was measured via two items: "How positive is this image?" and "How negative is this image?" (reverse-scored). All responses were on a scale from 1 ("Not at all") to 7 ("Very much so"). Crohnbach's alpha for the sociality items was .93; using principal components analysis (PCA), items were combined into one Sociality factor with a standard normal distribution. The valence items were correlated .79 ($p < .0001$) and were combined into one Valence factor with a standard normal distribution using PCA.

The Sociality and Valence factors were highly positively correlated ($r=.88$, $p <.0001$). As a result, selection focused on images with a standardized valence score between -1 and +1, neither extremely positive nor extremely negative. Within that set of items, images were categorized as "non-social" if the standardized sociality score was less than -1 and "social" if the sociality score was greater than +1. Unfortunately, these initial criteria yielded a total of only 12 images, 5 non-social and 7 social. The initial selection criteria were therefore broadened to include images between -1 and 1.2 in valence, reflecting the tendency to perceive neutral stimuli as slightly positive (Ito & Cacioppo, 2005). In addition, the pool of potential social and non-social images was broadened: images were categorized as "non-social" if they fell below -.67 on the social factor and "Social" if they were over .74. This produced a total image pool of 45 images, 22 non-social and 23 social. From this pool, preference was given to images with low standard deviations in Sociality ratings, to minimize potential ambiguity in interpretation, and create high face validity.

The final image pool was 8 social and 8 non-social images, which were used for the dot-probe task (see Figure 3.2 for a comparison of the selected and non-selected item Sociality and Valence ratings). Social images were rated as significantly more "social" than non-social images ($t=15.92$, $p < .0001$). Unfortunately, due to the strong correlation between sociality and positive valence, it was not possible to achieve a sample of images that differed significantly in sociality but not in valence: overall, the social images were rated as significantly more positively valenced than non-social images ($t=-5.35$, $p < .0001$). To address this problem, social and non-social images within the set were arranged in pairs that did not differ significantly from one another in valence, and only these pairs were presented in the dot-probe task. All social images were paired with more than one non-social image and vice versa, for a total of 23 image pairs.

Pictures deemed to be social included images of celebrations, a person relaxing and a person showing a Duchenne smile. Non-social pictures included utensils, neutral faces gazing directly at the participant, and faces with averted gaze. After selection, a

Gaussian histogram redistribution was used to equalized the overall brightness of the 16 images, in order to maintain contrast while eliminating the potential for response bias due to variations in overall image brightness (Agaian, Silver, & Panetta, 2007).

Task timing. Stimuli were presented in five blocks of 23 trials each; the number of trials set at 23 to avoid repeating an image pair during a block. In each block, a trial began with a fixation cross, after which pairs of stimuli were presented for either 45 ms (short duration block) or 750 ms (long duration block). Short trial timings were based on Trawalter et al. (2008), while long trial timings were based on Mather & Carstensen (2003). The stimuli were then replaced by a white dot on the right or left side of the screen. Participants pressed either the left or right key on the keyboard to indicate the location of the white dot; if the participant failed to respond by 900 ms after the appearance of the dot, the program moved on to the next trial. There was a 450 ms delay between the end of one trial and the beginning of the next trial. Participants were instructed to respond as quickly and accurately as possible. Image pairs were displayed in random order, with the social image randomly assigned to the left or right side of the screen each time the image pair was shown. All images pairs were shown in all blocks. The presentation order of short and long trial blocks was randomized, with each participant completing either two short trial blocks and three long trial blocks, or three short trial blocks and two long trial blocks. Participants completed six practice trials, three short and three long, before beginning the task.

Self-regulation. Both working memory capacity and emotion regulation were measured as components of the more general concept of self-regulation.

Working memory capacity. Working memory was measured using a 3-back task in which participants were presented, one by one, with a series of numbers and asked whether each number is the same as a number one, two or three trials back (Braver et al., 1997). Participants complete one block for practice, then 1-back, 2-back and 3-back blocks.

Emotion regulation. The ability to regulate emotional responses was measured using the four item emotional control scale (α = .69), which contains items such as "During an argument, I used and responded to reason even though I was feeling very upset" (Gyurak & Ayduk, 2008). Responses choices range from 1 ("Not at all descriptive") to 7 ("Very descriptive"). Scores on this scale have been positively associated with vagal tone (Gyurak & Ayduk, 2008).

Social closeness promotion. Interest in forming social connections with others was assessed through behavior and self-report when anticipating the interaction.

Behavioral measures of social closeness promotion. First, participants were asked to indicate their preferred modality for the coming interaction. In order from least closeness promoting to most: Online chatting (text-only), Skype (voice-only), video chat (voice and face) or face-to-face. Before choosing, participants were told that the face-to-face condition was full, but they may choose among any of the others. After choosing, the experimenter reported that a mistake was made, and all sections were full *except* for the face-to-face section. After participants were "assigned" to the face-to-face modality, they were led to an adjacent room, which was empty except for a stack of chairs, and asked to arrange the chairs in the room so that they and their partner can "talk comfortably." Using a variation of the procedure described by Goff, Steele & Davies (2008), the distance between the two chairs served as the second index of behavior promoting social closeness.

Affect and anxiety. After arranging the chairs, participants described their feelings about the upcoming interaction using the modified Differential Emotions Scale (Fredrickson, in press), with scale points ranging from 0, "not at all," to 4, "extremely," and the state version of the State-Trait Anxiety Inventory (Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983), with scale points ranging from 0, "not at all," to 3, "very much so." Each scale was comprised of one positive and one negative subscale. Scores were calculated by taking the mean of the items for each subscale, ending with four composite variables: Positive emotions (α = 0.87), negative emotions (α = 0.61), anxiety symptoms (α = 0.82) and relaxation (α = 0.91). Less anxiety about an social interaction predicts more positive responses from an interaction partner (Markey, Funder, & Ozer, 2003), and thus a greater likelihood of experiencing social closeness.

Procedure

Participants arrived at the lab and gave consent, then their picture was taken by a research assistant and they were told that their interaction partner had already arrived and was already in a cubicle.

Participants were then taken to a different cubicle, where they provided a four-minute free-respiration vagal tone baseline while alone in a small, quiet room, then completed measures of social attention and self-regulatory ability. When these measures were complete, participants were given a picture of an individual and told that later they would have a discussion of “racial issues” with this person, ostensibly another study participant, in another room.

White and black participants were randomly assigned to a “difficult interaction” condition (N=38) or an “easy interaction” condition (N=27). Because the ease or difficulty of the interaction depended on receiving a picture of a “same-race” or “different race” person as their future interaction partner, and the photographs were only of black or white students, all participants of other races or non-reported race (N=11) were by default assigned to the “difficult interaction” condition and randomly given a photograph of a black or white student. Pictures were gender-matched so that female participants were given female pictures and male participants male pictures.

After receiving the picture of their partner, participants were led to a separate room where two chairs were stacked in a corner, and asked to set up the chairs for their conversation while the experimenter brought their partner. After the chairs were set up, the participant completed a last questionnaire that contained manipulation checks, and the study ended. After an exit interview that included multiple probes for suspicion regarding the ‘upcoming interaction with partner’ story, the participant departed and the experimenter measured the distance and angle between the two chairs.

Results

Data Cleaning

Dot-probe. Analyses were based on response time to dots that appeared on the same side of the screen as a previously shown social or non-social image. Trials in which the participant did not respond or did not accurately locate the dot were excluded, as were the first and last trials, which were over three standard deviations above the mean response time and below the mean response time, respectively. To control for the disproportionate influence of extreme outliers, the data were Winsorised using the following procedure: The overall mean and standard deviation was calculated for each participant for slow and fast trials. Reaction times that were more than three standard deviations away from a participant's mean reaction time for each trial type were replaced with a value equal to the participant's mean response time for that trial type plus or minus three standard deviations, as appropriate.

The remaining fast and slow trials were further divided into trials where the dot appeared on the same side as a social picture ('social trials') and trials where it appeared on the same side as a non-social picture ('non-social trials'). Response times were averaged per participant across combinations of fast/slow and social/non-social trials, creating four mean values for each participant: Mean response time for fast social trials, fast non-social trials, slow social trials and slow non-social trials. Finally each participant's mean 'social' response time was subtracted from their mean 'non-social' response time, in order to create a "social attention bias" score for fast and slow trials. If participants responded more quickly to social trials than the non-social trials, their bias score was positive; if they responded more quickly to non-social trials than to social trials, their bias score was negative. Congruent with other dot-probe research, bias scores for fast trials are interpreted as an indicator of non-conscious responding, whereas bias scores for slow trials indicate orienting guided by conscious choice (Richeson & Trawalter, 2008).

N-back task. The first four trials were excluded due to unusually slow reaction times. Mean accuracy scores were computed for 1-back, 2-back and 3-back blocks.

Experimental Manipulation Checks

White participants only. Because discussions of race involving both white and black discussants are more stressful for whites, only data from white participants were initially analyzed (Trawalter & Richeson, 2008). There were 51 white participants, 22 assigned to the "same race" condition and 29 in the "different race" condition.

Experimenters' debriefing notes and the manipulation check questionnaire were consulted to exclude participants who did not believe the cover story. Two sets of criteria were used: A "wide" standard where participants were retained unless they explicitly articulated that they didn't think they were going to have a conversation, and a "narrow" standard where participants were excluded if they expressed uncertainty about whether they were going to have a conversation. The proportion of participants expressing skepticism did not differ significantly across conditions using either criterion. Using the "wide" standard, nine participants were excluded, 5 from the "different race" condition and 4 from the "same race" condition (p = .36), for a final N of 43. Using the "narrow" standard, 24 participants were excluded, 12 from the "different race" condition and 12 from the "same race" condition (p = .93), for a final N of 27.

Independent samples t-tests were used to compare behavioral indices of social closeness promotion and self-reported affect and anxiety across conditions. Results using both exclusion criteria are shown in Table 3.1. When using the wide criterion, there were no significant differences between conditions for any of the variables assessed. Two marginally significant differences were found when using the narrow criterion, both in a direction contrary to what was anticipated: Participants in the “different race” condition self-reported marginally fewer negative anxiety symptoms (such as shortness of breath; $p = .11$) and marginally more positive emotions ($p = .08$). No differences were found in the behavioral measures.

Black and white participants. Next, the same analyses were conducted using both white and black participants, to check for potential differences by condition that may have been masked by the small size of the white participant sample. Data from participants of other races and those who declined to report their race were excluded because their race would have been confounded with condition assignment. The total available N was 64. Using the “wide” standard, nine participants were excluded, 6 from the “different race” condition and 4 from the “same race” condition, for a final N of 54. Using the “narrow” standard, 26 participants were excluded, 13 from the “different race” condition and 13 from the “same race” condition, for a final N of 38. Results from these analyses are shown in Table 3.2. No significant differences between conditions were found for either exclusion criterion in either behavior or self-reports.

Absolute levels of social closeness promotion. As shown in Tables 3.1 and 3.2, the majority of participants indicated a moderate amount interest in achieving social closeness in the upcoming interaction. Edward Hall’s research on proxemics provides norms for different forms of “interpersonal space” among white Americans (Hall, 1966). He divides interpersonal space into “intimate distance,” standing less than 18 inches apart; “personal distance,” 18 inches to four feet apart; “social distance,” four feet to eight feet apart; and “public distance,” more than eight feet apart. Participants in this study situated their chairs approximately 36.5 inches apart, regardless of condition. This falls well within the "personal distance" category, which is used for conversations with friends and associates, as well as group discussions (Hall, 1966), and suggests relative comfort with the upcoming interaction.

Self-report data is congruent with this interpretation. Across conditions, participants reported feeling at most "somewhat" anxious (range 0-1) and "a little bit" negative (range 0-1), as well as feeling, on average, "moderately" relaxed (range 0-3). The only potential indicator of unease concerning the upcoming interaction comes from the low scores for positive emotions; on average, participants reported feeling only "a little bit" positive (range 0-3) as they waited to meet their conversational partner.

Self-report data was not significantly correlated with any of the behavioral measures of social closeness promotion and choice of conversational modality was uncorrelated with chair distance (see Table 3.3).

Summary. Based on the results described above, the race-based social anxiety manipulation did not appear to be successful. Thus, it is not possible to test the hypotheses linking vagal tone, social attention and self-regulation to social closeness promoting affect and behaviors when under social stress. The self-report and behavioral measures of social closeness promotion were also uncorrelated with one another. Potential reasons for the failure of the race-based manipulation are detailed in the discussion section.

Trait-Level Analyses

Further analyses address hypotheses regarding trait-level associations between vagal tone, self-regulation, social attention and self-reported anxiety. Behavioral measures of social closeness promotion were not used due to concerns about the validity of the measures.

I. Vagal tone is correlated with attentional bias toward social stimuli and self-regulation.

II. Vagal tone, attentional bias toward social stimuli and self-regulation are correlated with reduced anxiety about social interactions.

III. The relationship between vagal tone and anxiety about social interactions is mediated by both self-regulation and attentional bias toward social stimuli.

Because the majority of participants appeared convinced that they would be having a conversation with someone, the anxiety measures will be retained but condition information will be ignored. In other words, the hypothetical future conversation framing will be used to study the affective response and anxiety or relaxation reaction to anticipating a conversation with a stranger on a sensitive topic. Since participant race and skepticism regarding identity of the conversation partner no longer affect the hypotheses to be tested, analyses from this point onward include all participants who meet the "wide" inclusion criterion, regardless of race (N=63, 62.5% female, 65.6% white, 20.3% black, 3.1% Asian, 3.1% Hispanic, 1.6% "mixed").

I. Vagal tone is correlated with attentional bias toward social stimuli and self-regulation. Vagal tone was significantly correlated with performance on slow dot-probe trials (*r*=0.259, *p*=.04), but not fast trials (r=.14, p=.27). Contrary to previous studies (Hansen et al., 2004; Thayer & Brosschot, 2005), vagal tone was not significantly correlated with working memory as measured by the n-back task (1-back *r*=.12, *p*=.37; 2-back *r*=-.05, *p*=0.71; 3-back *r*=-.14, *p*=.92) or with self-reported emotion regulation (*r*=-.08, *p*=.54).

II. Vagal tone, attentional bias toward social stimuli and self-regulation are correlated with lower anxiety and more positive emotions when anticipating a social interaction. High vagal tone predicted greater relaxation when anticipating an upcoming social interaction (r=.32, p=.02), but did not predict affect or negative anxiety symptoms. Responses to the slow attentional bias trials were correlated with fewer symptoms of anxiety (*r*=-.39, *p*<.01), as well as marginally greater relaxation (*r*=.25, *p*=.06). Responses to the fast attentional bias trials were not significantly correlated with any measures of self-reported anxiety or affect. Working memory, as measured by the n-back task, was uncorrelated with anxiety or affect. Emotion regulation predicted more positive emotions (*r*= .32, *p* < .05) and marginally more relaxation (*r*=.22, *p* < .10).

III. The relationship between vagal tone and anxiety about social interactions is mediated by both self-regulation and attentional bias toward social stimuli. A structural equation model was fitted to test the proposed multiple mediational relationships. Initial tests in AMOS revealed multivariate and univariate non-normality in the data, with the majority of measured variables showing critical ratios greater than 2 or less than -2 in skew or kurtosis. Accordingly, analyses will employ bootstrapping with

10,000 samples in order to generate bias-corrected standard errors. The Bollen-Stine bootstrap will be used to generate the chi-square test of model fit (Bollen & Stine, 1992).

Because bootstrapping in Amos requires a dataset without missing observations, missingness was filled in using regression-based imputation. The following variables were used as both regressors and targets of the imputation: Negative emotions, positive emotions, negative anxiety subscore, positive anxiety subscore, suspicion concerning the cover story, emotion regulation, vagal tone, slow dot-probe trial score and fast dot-probe trial score.

Measurement model. To maximize variance in the dependent variable in the face of the low levels of anxiety reported by most participants, "Anxiety" was modeled as a latent variable with three predictors: The negative subscale of the State Anxiety Inventory (SAI), the positive subscale of the SAI (reversed), and the negative emotions subscale of the modified Differential Emotion Scale. The positive emotions subscale of the mDES was not included in the latent variable as positive emotions are conceptually distinct from anxiety (Kashdan & Steger, 2006). The variances of the three predictors were uncorrelated. The measurement model for anxiety fit well, with RMSEA of .000, CFI of 1 and Bollen-Stine bootstrap p=.58 with a bootfactor of 1. The regression weight of Anxiety on the negative subscale of the SAI was fixed to one and the standardized regression weights for the other two indicators were significant (negative emotions b= .83, $p < .001$; positive SAI subscale b= -.55, $p < .001$), suggesting that the three indicators are appropriately correlated with the Anxiety latent variable.

Structural model I. Having established the measurement model, a structural model was fitted with vagal tone as an exogenous variable predicting performance on slow attentional trials (“Social attention”), emotion regulation and anxiety. The endogenous variables of social attention and emotion regulation also predicted anxiety. Working memory was not included as a predictor as scores on the n-back were uncorrelated with vagal tone and anxiety in previous analyses. The full structural equation model, including both the measurement and structural relationships, is shown in Figure 3.3. Suspicion of the cover story was included as a covariate for anxiety and is not shown in the model figure.

Fit for the full model was acceptable, with RMSEA 0 .06 (90% CI: .00 to .14), CFI =.965 and Bollen-Stine bootstrap *p*=0.33. The model explained 14.3% (90% CI: 1.9% to 22.1%) of the variance in anxiety scores. Standardized regression weights are shown in Figure 3.3.

Mediational tests for social attention and emotion regulation were run according to the guidelines provided in Rucker, Preacher, Tormala, and Petty (2011). Rucker et al. advise researchers to focus on the size of indirect effects as an index of mediation; accordingly, we will report direct and indirect effects here rather than computing the ratio of indirect to total effect as is done in the traditional Sobel test framework

To explore the possibility of mediation, the regression weights for the paths linking the exogenous variable to the mediator and the mediator to the outcome variable must both be significant (Rucker et al., 2011). In the current model, both of the mediational paths involving social attention are significant, while neither of the mediational paths involving emotional control are significant. Since both paths must be significant in order to investigate mediation, further analyses will focus only on social attention.

Structural model II. To statistically test the significance of the indirect effect of vagal tone on anxiety through social attention in AMOS, a new SEM was fitted. The new structural equation model is identical to the first, with the exception that emotional control is an exogenous predictor of anxiety and uncorrelated with vagal tone. This was necessary to isolate the role of social attention, as AMOS output gives only the total indirect effect over all mediators combined. Model fit was acceptable, with RMSEA 0 .05 (90% CI: .00 to .13), CFI =.970 and Bollen-Stine bootstrapped p = 0.37. A nested likelihood ratio test comparing the old and new models indicates that the more parsimonious model fits the data equally well ($\chi^2(1)= 0.509$, $p = .48$). The model explained 14.1% of the variance in anxiety scores, with a 90% confidence interval from 1.9% to 22.1% ($p = .01$).

As shown in Figure 3.4, the paths from vagal tone to social attention and from social attention to anxiety were both significant, allowing further tests to explore the potential for mediation.

The standardized total effect of vagal tone on anxiety was non-significant ($p = .62$), with a 90% confidence interval of -.263 and .144. Simulation work by Rucker et al. has shown that significant indirect effects can exist, even in the absence of a significant total effect, and that this is most often the case when the population value of the total effect is smaller than the population value of the two paths that make up the mediational effect (2011). In the case of these analyses, it is reasonable to expect that the relationship between a trait variable such as vagal tone and a state variable such as momentary anxiety would be weaker than the relationship between two trait variables such as vagal tone and social attention. Thus, further investigation of the indirect effect is deemed appropriate even in the absence of a statistically significant total effect.

The bias-corrected 90% confidence interval for the standardized indirect effect of vagal tone on anxiety was -.192 to -.018, suggesting that for every one standard deviation increase in vagal tone, anxiety would decrease by between .018 and .192 of a standard deviation, indirectly through social attention (p= .02).   The statistical evidence is consistent with a mediational relationship where vagal tone predicts social attention, which in turn predicts lower anxiety in the face of an upcoming social interaction.

Alternate model 1: Does vagal tone mediate the relationship between social attention and anxiety? This model is identical to Figure 3.4 with the exception that social attention is an exogenous variable that predicts vagal tone, now an endogenous variable. Because both models have the same variables and the same number of paths, model fit is identical. The direct effect of social attention on anxiety is significant and positive (p = .02), while the direct effect of vagal tone on anxiety is non-significant (p = .91). The indirect effect of social attention on anxiety through vagal tone is not significant (p=.83). It is apparent that vagal tone does not mediate the relationship between social attention and anxiety about an upcoming interaction.

Alternate model 2: No mediation. This model is identical to Figure 3.4 with the exception that the path between social attention and vagal tone is constrained to zero and both are exogenous variables. Fit for the model without mediation is not as good as the mediational model, but is still acceptable, with RMSEA 0 .083 (90% CI: .00 to .15), CFI =.922 and Bollen-Stine bootstrapped p = .20.   A nested likelihood ratio test comparing the old and new models indicates that the model without mediation does not fit the data as well as the model including mediation (χ^2(1)= 5.500, p = .02).

Discussion

Failure of the Experimental Manipulation

Contrary to previous research in this area (Trawalter & Richeson, 2008), believing that one was about to have a conversation about “racial issues” with someone of a different race was no more anxiety-inducing for participants than believing the conversation was to be with someone of the same race. Moreover, participants did not appear to experience much anxiety at all, despite the fact anticipating a discussion of “racial issues” should have been moderately anxiety-producing even for homogenous-race pairs. Four potential explanations for this failure to induce anxiety include differences in the racial demographics of UNC compared to other universities, students’ potential previous opportunities for interracial interactions, the role of motivation to appear unprejudiced, and potential weaknesses in the experimental cover story.

Perhaps the participants, as UNC students, were more experienced in navigating interracial interactions than the average American university student, and thus did not find the race manipulation anxiety-inducing. Reference to existing demographic data for UNC relative to the United States as a whole does not support this explanation. The percentage of first-year students enrolled at UNC in 2011 who identified as “White or European American” and “Black or African American” at UNC-Chapel Hill (67% white, 11% black, Farmer , 2011) did not differ greatly from the United States average (78.1% white, 13.1% black, U.S. Census Bureau Population Estimates Program, 2011b). In addition, racial diversity among university undergraduates does not appear to be related to replicating the interracial stress effect. Studies at both Ohio State (C. S. Johnson, Olson, & Fazio, 2009) and Dartmouth (Richeson & Trawalter, 2005; Trawalter & Richeson, 2006) have found that interactions between blacks and whites are more stressful than racially homogenous interactions. In 2011, fewer African-American undergraduate students enrolled at UNC as first-year students than at The Ohio State University (17.6%, Undergraduate Admissions and First Year Experience, 2011) but more enrolled at UNC than Dartmouth College (8%, Office of Institutional Research , 2011). The demographic similarity of UNC to the U.S. as a whole, as well as the variability in racial demographics among universities that have replicated the stressful interracial interaction effect, suggests that the racial makeup of UNC students cannot account for the failure to find an effect.

Perhaps, then, UNC students experienced greater diversity in their lives prior to attending university. Natives of North Carolina made up 80.7% of the UNC undergraduate population in 2011 (Office of Institutional Research and Assessment), and 22% of North Carolina residents identify as African-American, higher than the national average of 13.1% (U.S. Census Bureau, 2011b). Potentially, then, UNC students may have been less anxious about the upcoming racial conversation because they were more practiced at interracial interactions. In support of this point, only 12.4% of Ohio residents identified as African-American in the 2010 Census (U.S. Census Bureau, 2011a), suggesting that, as 78% of Ohio State first-year students are Ohio residents (2012), Ohio State students on average have less experience with interracial contacts than UNC students. Unfortunately, as only 20.3% of Dartmouth College students are residents of

New England, it is difficult to compare the relative racial diversity of Dartmouth students' backgrounds to those at UNC (Class profile , 2011). It is possible that UNC students' experiences growing up in an area with a larger African-American population contributed to their lack of stress at the prospect of an interracial interaction.

Perhaps participants did not show increased anxiety in the interracial interaction condition because they were not concerned about appearing prejudiced. Motivation to respond without prejudice is associated with heightened anxiety and physiological stress responses during interracial interactions (Trawalter, Adam, Chase-Lansdale, & Richeson, 2012). Unfortunately, to avoid demand effects related to racial attitudes, neither prejudice nor motivation to respond without prejudice were measured in the study. Thus, it is not possible to use these data to test whether the effect of the manipulation was moderated by motivation to respond without prejudice.

Finally, participants may not have shown anxiety because the cover story was unconvincing. We screened out participants who reported skepticism about the 'future conversation with partner' story, but it is possible not all participants reported their skepticism. No participant reported doubting whether their partner would be of the same race as the picture they had been shown. The cover story did not provide any details about the topic of conversation beyond "racial issues," and perhaps that descriptor was too vague to create anxiety. Alternatively, knowing they would be discussing "racial issues" may have ironically made participants in the interracial interaction condition less anxious, as they would not have to suppress all race-related cognitions during their conversation in order to avoid appearing prejudiced.

Trait Analyses

People who are high in vagal tone are rated, by themselves and by others, as more socially connected and empathetic than those low in vagal tone (Eisenberg et al., 1995; Fabes, Eisenberg, & Eisenbud, 1993; Smith et al., 2011). Even so, the mechanisms that translate activity of the vagus into good relationships and positive social behaviors have remained an open question. Social openness, marked in part by a tendency to preferentially attend to social stimuli, may be one way that vagal tone increases the likelihood of social success. In this study, vagal tone predicted greater attention to social stimuli as compared to affectively-matched non-social stimuli. In turn, preferential social attention predicted lower self-reported anxiety when anticipating a social interaction with a stranger. The indirect effect of vagal tone on anxiety via social attention was significant, suggesting that, for these participants, vagal tone was associated with lower anxiety because vagal tone predicted greater attention to social stimuli.

In this study, anxiety about an upcoming social interaction was used as an indicator of social closeness motivation, as anxiety about an interaction predicts negative responses from an interaction partner (Markey et al., 2003). However, anxiety is more closely related to avoidance motivation (Elliot & Church, 1997). Social avoidance motivation prospectively predicts loneliness and negative evaluations from peers (Crocker, 2011); however, a lack of loneliness may not be equivalent to the presence of social closeness (Hawkley & Cacioppo, 2010). Future studies should use a less ambiguous measure of social behavior that leads to positive social outcomes- for example, a participant's behavior during a social interaction could be rated according to how likeable the participant appears and how much their interaction partner would like to see them again. These ecologically valid measures of success in pursuing social closeness would do much to confirm the importance of social attention and vagal tone in relationship formation.

Contrary to previous empirical work (Segerstrom & Nes, 2007), performance on the working memory task was not associated with vagal tone. Working memory was also not correlated with anxiety when anticipating a social interaction or emotion regulation, casting doubt on the validity of the measure. As the n-back is a well-known and validated measure of working memory, the most likely explanation for the failure to replicate is a flaw in the implementation of the measure. Participants completed the n-back in the controlled environment of a laboratory cubicle, however, they were not monitored while they completed the task, and variables such as the position of their head, the direction of their gaze and the specific fingers used to respond to the N-back stimuli were not rigidly controlled by the experimenter. All of these factors could have introduced error into the paradigm.

This study is the first to empirically link vagal tone to social attention in a neurotypical sample. Moreover, social attention mediated the relationship between vagal tone and anxiety when anticipating a social interaction. The tendency to prioritize social information in the environment, then, may be a mechanism of vagal influence on social behavior. This evidence suggests that vagal tone may represent a heritable, physiological state that evolved to motivate social affiliative behaviors in part through the regulation of attention, facilitating social bonding and promoting health.

CONCLUSION

From an evolutionary perspective, a heritable tendency to affiliate with others would have been a valuable contribution to reproductive success. The Socio-Autonomic Spiral Model of Social Closeness and Health describes a heritable, self-sustaining psychophysiological system, based on the vagus nerve, that promotes social affiliation in safe situations, resulting in social bonds. The vagus promotes social affiliation by enhancing self-regulatory capacity and directing positive attention toward social stimuli during moments of safety. Self-regulation and positive social attention play important roles in forming and maintaining satisfying social bonds. Social bonds, in turn, increase feelings of safety and well-being, leading to more vagal activity. I have proposed that these are mutually-enforcing causal relationships that unfold over time in a spiral pattern where change in one element of the spiral, such as social closeness, flows onward to influence to other elements of the spiral, such as vagal tone. In such a spiral, even small, momentary changes can accumulate and compound, ultimately transforming a person's social relationships and consequentially impacting health.

The bi-directional relationships between social closeness and vagal tone predicted by the model were tested in two separate studies. The prediction that social closeness increases vagal tone by enhancing psychological well-being was tested in a longitudinal study that experimentally increased social closeness in participants for eight weeks. Congruent with SASM, social closeness increased positive emotions, and in turn positive emotions predicted increases in vagal tone by the end of the study. However, both my own previous work (Kok, Coffey, et al., in press; Kok & Fredrickson, 2010) and the SASM also predicted that vagal tone upon entering the study would moderate the effectiveness of the intervention, with higher vagal tone accelerating participants' positive emotional growth. Vagal tone was predicted to moderate the effect of the intervention because individuals with higher self-regulation would be more compliant with the study instructions, and individuals who habitually attended to social stimuli would be primed to respond to opportunities to increase in social closeness, such as the experimental intervention.

Vagal tone did not moderate the effect of the social closeness intervention in this study. Reasons for this failure to replicate come from the reasoning behind the original moderation hypothesis, in combination with the unique characteristics of the social closeness intervention. In the previous study (Kok, Coffey, et al., in press), the social closeness intervention was seven weeks of training in loving-kindness meditation, a moderately demanding exercise that requires persistence and the ability to regulate emotions. In contrast, the current social closeness intervention consisted of two brief, multiple-choice questions delivered via email each day. Vagal tone may have moderated the effects of LKM and not the emailed intervention because LKM benefitted from higher self-regulatory capacity. This explanation is undercut, however, by a previous study (Kok & Fredrickson, 2010) where participants in the control group showed increases in positive emotions that were significantly predicted by vagal tone, an effect attributed to daily completion of the same multiple choice questions about social closeness as were used in the present study.

Alternatively, positive social attention may have played a role in amplifying the effectiveness of LKM. Part of LKM practice is generating feelings of love and kindness toward a specific person. Perhaps individuals who are more likely to attend to social information were better able to picture the target of their meditation, or had more targets to choose from. In contrast, the emailed intervention asked about participants' experiences across multiple social interactions that day, and did not require focus on any individual interaction or individual. Thus, a tendency to attend to social information would not have amplified the effect of the email intervention, but might have done so for the LKM.

Both of these explanations suggest that vagal tone will only encourage social closeness in circumstances where self-regulation or positive social attention can play a role. For example, vagal tone may predict higher likability ratings from strangers due to a tendency to make more eye contact during interactions, but be unrelated to likability ratings from a third party observing the interaction who is not receiving eye contact. Further studies can explore the conditions where vagal tone is socially advantageous in order to understand what aspects of social behavior are consequentially affected by the vagus.

The prediction that vagal tone increases social closeness through self-regulation and positive social attention was tested in an "anticipated social interaction" paradigm. Less anxiety about a social interaction predicts positive outcomes in the interaction (Markey et al., 2003), and therefore it was expected that vagal tone would negatively predict anxiety, mediated by self-regulation and positive social attention. In fact, vagal tone, emotion regulation and positive social attention predicted less self-reported anxiety when anticipating a social interaction, but self-regulation as measured via a working memory task (the N-back) did not. Furthermore, positive social attention mediated the relationship between vagal tone and anxiety, but emotional control did not. This study provides the first empirical evidence linking vagal tone to positive social attention in a neurotypical sample, and also finds that positive social attention is correlated with less anxiety about an upcoming interaction. These findings provide a first look at the potential mechanisms that translate activity of the vagus nerve into positive social outcomes.

On the other hand, the lack of an effect for self-regulation is surprising, as vagal tone has been correlated with self-regulation and emotion regulation in adults and college students, using behavioral, neurological and self-report paradigms (Ahs, Sollers, Furmark, Fredrikson, & Thayer, 2009; Segerstrom & Nes, 2007). Failure to replicate a well-known association between traits typically suggests an error in operationalization or measurement, or insufficient power. In fact, performance on the n-back task of working memory used to assess self-regulation was uncorrelated with all other study-related measures reported here, including emotion regulation. Within the n-back, performance in 1 back trials was uncorrelated with performance on 2-and-3-back trials, which is also unusual. A new study currently under IRB review will re-address the association between vagal tone, self-regulation, social attention and social behavior: This study will have an N of 100, a different implementation of the n-back task, multiple other behavioral measures of self-regulation and emotion regulation, and two weeks of daily reported social closeness. My intent is to use the measures of self-regulation to create a latent variable that excludes bias due to a specific measurement method, then re-test the hypotheses from the laboratory study.

Summary

. The relationship between social closeness and health has often been viewed as unidirectional, with social closeness leading to better health, and with little understanding of the mechanisms that might drive this relationship. In this dissertation, I have argued that social closeness and health are bi-directionally and reciprocally linked, and have proposed multiple potential mechanisms to drive the relationship. In one study, social closeness increased vagal tone through changes in positive emotions, while in another, vagal tone predicted positive attention to social stimuli, which in turn predicted a higher likelihood of positive social outcomes. These findings are encouraging in their support for the Socio-Autonomic Spiral Model of Social Closeness and Health. Below, I discuss the implications of SASM within the broader social closeness and health literature.

Open Questions and Implications

The costs of positive social behavior

Positive social behavior is paradoxical in many ways. Prosocial behavior and approach behaviors may be stressful and can also be costly, as the person gives some of their resources to help another or must cope with an unfamiliar or unpredictable situation (Brown & Brown, 2006). The types of behaviors associated with high vagal tone- empathizing with the suffering of another, inhibiting aggressive responses, down-regulating negative emotions- are also associated with physiological or psychological stress (Amodio, Master, Yee, & Taylor, 2008; Helsen, Goubert, Peters, & Vlaeyen, 2011;

Richards & Gross, 1999). Stress, in turn, is associated with vagal withdrawal, and repeated exposure to stressors predicts low vagal tone (El-Sheikh, Harger, & Whitson, 2001; El-Sheikh & Whitson, 2006; Whitson & El-Sheikh, 2003). How, then, can empathy and behavioral inhibition, which increase stress, be associated with high vagal tone?

While helping, empathizing and exercising self-control can be stressful, they are also complex actions that take place in a larger social context that often rewards prosocial behavior and self-regulation. In addition, unpublished data from one of my previous studies suggests that vagal tone is correlated with ascribing high importance to behaving morally (Kok, Unpublished data), so these potentially costly behaviors may be ultimately positive because they are affirm personal values (Creswell et al., 2005). Other, speculative explanations include that people with high vagal tone are buffered against the stressors they invite because of their fast and flexible autonomic responses, which minimize physiological carry-over from past stressors. Other physiological systems that support social behavior, such as the oxytocin-driven calm-and-connect (Uvnas-Moberg, 2003) or tend-and-befriend (Taylor et al., 2000) system, may also buffer against stress caused by engaging in positive social behavior.

Re-thinking the parasympathetic nervous system

Studying social relationships and health can be much like a blind woman studying an elephant: It's easy to take hold of one part, like vagal tone and perceived social closeness, and forget that it is but one piece of a much larger animal. Researchers are also finding reciprocal links between inflammation (Miller et al., 2009) and social behavior, and oxytocin (Uvnas-Moberg, 2003) and social behavior. In addition, it is becoming apparent that both inflammation (Thayer et al., 2011; Thayer & Sternberg, 2010) and oxytocin (Kemp et al., 2012) are linked to vagal tone, as well as to one another (Gutkowska & Jankowski, 2012; Pittman, 2011).

The "elephant," in this case, might well be the parasympathetic nervous system (PNS) as a whole. While the sympathetic nervous system (SNS) has long been considered an integral part of psychological experience (Schachter & Singer, 1962), the parasympathetic has rarely been associated with psychological experience except in research on stress recovery, where its purpose is to counteract SNS activity (Fredrickson & Levenson, 1998). The PNS, of which the vagus is a major part, regulates oxytocin secretion (Uvnas-Moberg, 2003) and the inflammatory response (Thayer et al., 2011). It seems unlikely that the human body would evolve three distinct systems for regulating social behavior: The vagus for social approach, oxytocin for trust and generosity in existing relationships (Bartz et al., 2011) and inflammation for social withdrawal (Eisenberger et al., 2010; Inagaki et al., 2012). All three may be coordinated by the PNS, working together to create large, protective and supportive social groups through relationship building behaviors, and protecting those groups from infection by promoting withdrawal from social interactions when ill.

Conceptualizing the PNS as an active as well as reactive system mirrors the emerging consensus that positive states such as positive emotions and feelings of security, which often accompany or initiate PNS activation, do not necessarily lead to passivity, but to generative, creative, resource-building action aimed at long-term rewards rather than short-term consequences (Fredrickson, 1998). The PNS may motivate actions that promote long-term growth and survival, balancing SNS-driven short-term responses to immediate threats. Research that utilizes measures of both PNS and SNS may be particularly well-suited to investigate this possibility; PNS activity in the absence of SNS activity may drive positive feelings and generative behavior, while simultaneous PNS and SNS activity may reflect the more traditional understanding of the PNS as a calming system.

Conclusions

There is no doubt that social closeness and health are inextricably linked, but the nature of this link has proved difficult to unravel. In this work, I have attempted to model this linkage as a reciprocal and bi-directional spiral between social closeness and health. In one study, I hypothesized and found that experimentally induced changes in social closeness led to changes in positive emotions, which resulted in changes in vagal tone. However, contrary to the predictions of the Socio-Autonomic Spiral Model of Social Closeness and Health, and to my own previous empirical findings (Kok, Coffey, et al., in press), the effects of the social closeness intervention were not moderated by starting level of vagal tone.

In a second study, I tested the prediction of SASM that vagal tone would be associated with decreased anxiety about social interactions, and that this decrease in anxiety would be mediated by self-regulatory ability and social openness, assessed as a preference for social images over non-social images. Vagal tone predicted decreased anxiety about an upcoming social interaction, and this effect was mediated by social openness. However, contrary to SASM and to other empirical work (Segerstrom & Nes, 2007), vagal tone was not correlated with self-regulation or emotion regulation, nor were the measures of self-regulation and emotion regulation related to anxiety about the upcoming social interaction, again contrary to previous empirical work (Movius & Allen, 2005; Smith et al., 2011; Trawalter et al., 2009; Vohs et al., 2005).

Using the conceptual framework of the Socio-Autonomic Spiral Model of Social Closeness and Health, this work has shown that experimentally manipulated social closeness increases psychological well-being, which increases activity of the vagus nerve, a marker of autonomic flexibility associated with a wide range of positive health outcomes. Activity of the vagus at rest, in turn, was associated with openness to social opportunities and decreased anxiety about social interactions. In combination, the findings of these two studies suggest that the close association between social closeness and health may be due in part to the accumulation of small changes in behavior, physiology or psychological state that cause down-stream changes in other elements of the socio-autonomic spiral. Such small changes compound over time, eventually manifesting in large individual differences in social closeness and health.

TABLES

Table 2.1: Multilevel modeling of pilot test data

	Positive emotions	Negative emotions
Time	-0.05***	-0.03*
Condition	-0.28	-0.06
Time*condition	0.03*	0.003
Weekend	0.12**	-0.07**
$Time^2$	0.001***	0.001*
$Time^2$*condition	-0.001	0.000

Note: *p <= .05, **p <.01, ***p<.0001

Table 2.2: Latent growth curve model for positive emotions

Path	*b*(SE)
a	-.02(.13)
b	.38(.18)*
c	-.15(.17)
d	-.10(.26)
e	.13(.16)
f	.02(.23)

g	-.31(.20)
h	.65(.26)*
RMSEA/	.082/
90% CI	.045-.114
CFI	.945
TFI	.938

Note: Values are standardized. *p <= .05

Table 3.1: Affective and behavioral measures by condition for Caucasian participants only

	Wide filter			Narrow filter		
	Same race	Different race	p-value	Same race	Different race	p-value
Anxiety measures						
SAI Negative Subscale	0.59	0.47	0.28	**0.64**	**0.43**	**0.11**
SAI Positive Subscale	1.64	1.64	0.99	1.41	1.7	0.22
Social distance measures						
Distance between chairs (in.)	36.67	36.18	0.86	38.4	36.5	0.65
Choice of video chat	0.28	0.48	0.2	0.3	0.44	0.5
Choice of phone chat	0.17	0.04	0.23	0.2	0.06	0.3
Choice of IM chat	0.56	0.48	0.63	0.5	0.5	1
Emotion measures						

Negative	0.35	0.34	0.93	0.38	0.34	0.74
Positive	1.08	1.26	0.45	**0.93**	**1.44**	**0.08**

Note: **Bolded** values indicate marginally significant differences.

Table 3.2: Affective and behavioral measures by condition for African-American and Caucasian participants

	Wide filter			Narrow filter		
	Same race	Different race	p-value	Same race	Different race	p-value
Anxiety measures						
SAI Negative Subscale	0.58	0.46	0.21	**0.62**	**0.43**	**0.10**
SAI Positive Subscale	1.67	1.68	0.94	1.52	1.74	0.36
Social distance measures						
Distance between chairs (in.)	37.00	37.34	0.90	38.91	37.85	0.78
Choice of video chat	0.35	0.41	0.60	0.36	0.38	0.92
Choice of phone chat	0.13	0.06	0.42	0.14	0.08	0.58
Choice of IM chat	0.52	0.52	0.97	0.50	0.54	0.81
Emotion measures						
Negative	0.35	0.34	0.89	0.35	0.35	0.96
Positive	1.13	1.24	0.61	1.07	1.36	0.29

Note: **Bolded** values indicate marginally significant differences.

FIGURES

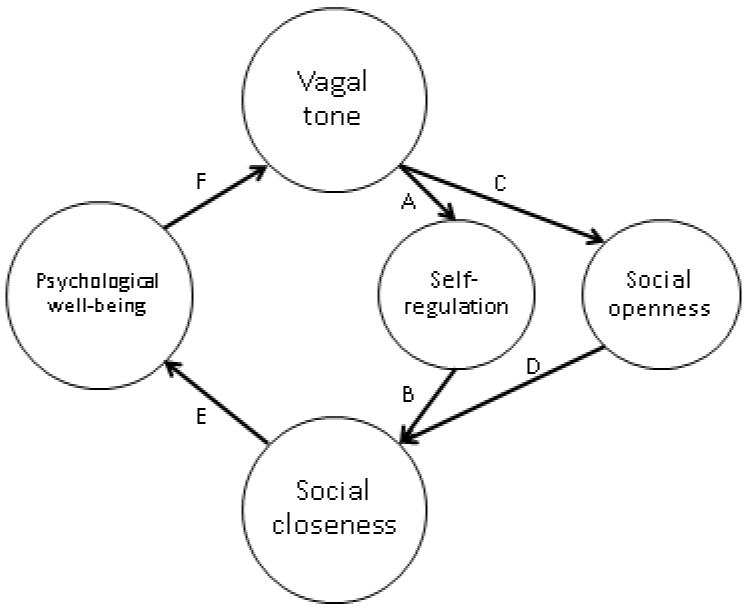


Figure 1

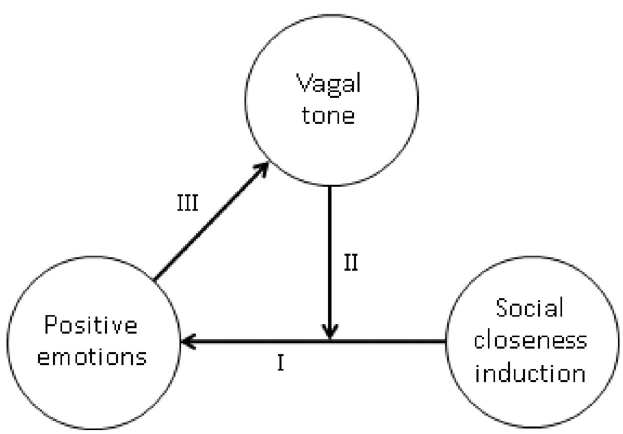
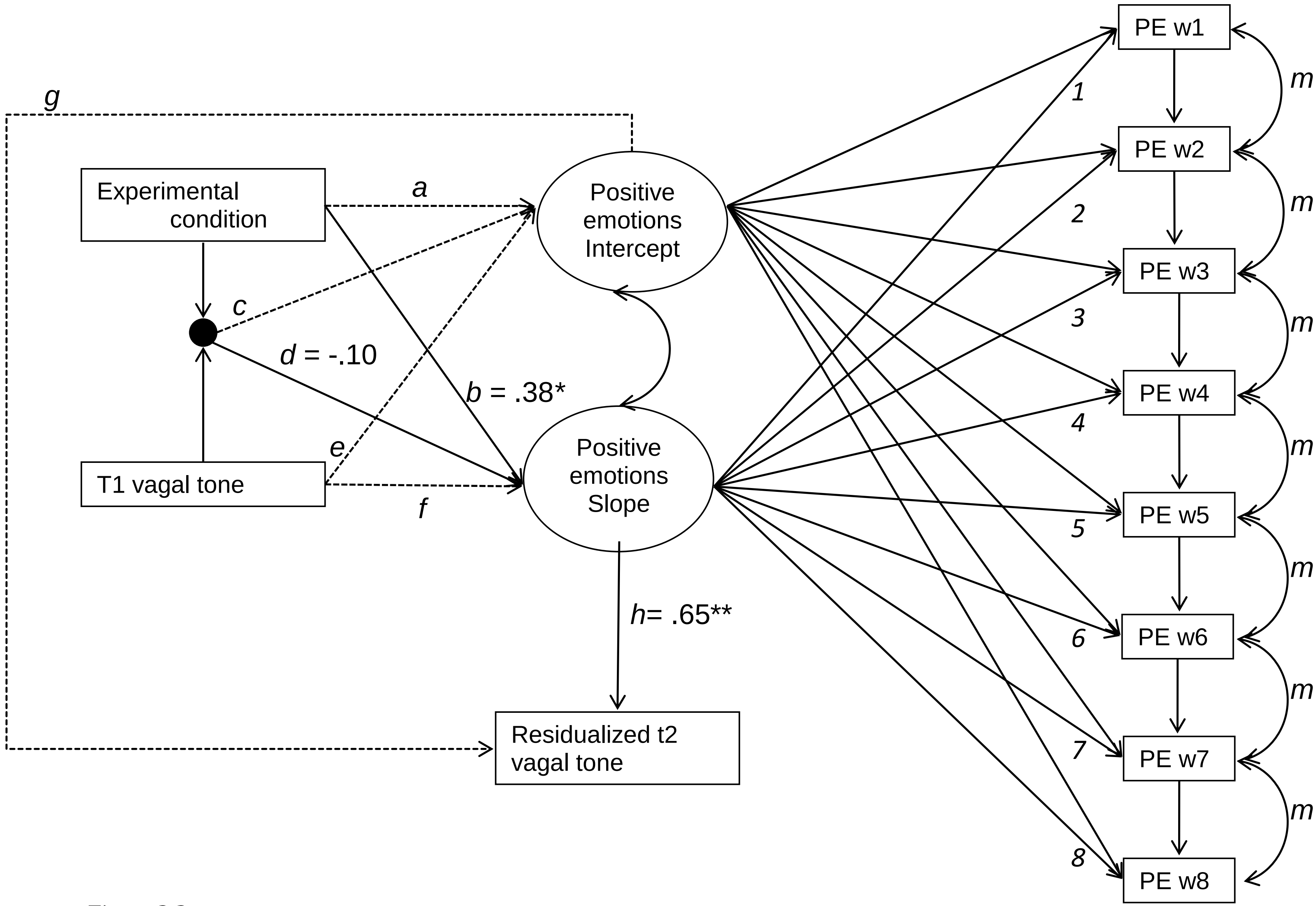


Figure 2.1


g
Experimental condition
a
c
d = -.10
b = .38*
e
f
T1 vagal tone
Positive emotions Intercept
Positive emotions Slope
h= .65**
Residualized t2 vagal tone
PE w1
PE w2
PE w3
PE w4
PE w5
PE w6
PE w7
PE w8
1
2
3
4
5
6
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8
m
m
m
m
m
m
m

Figure 2.2

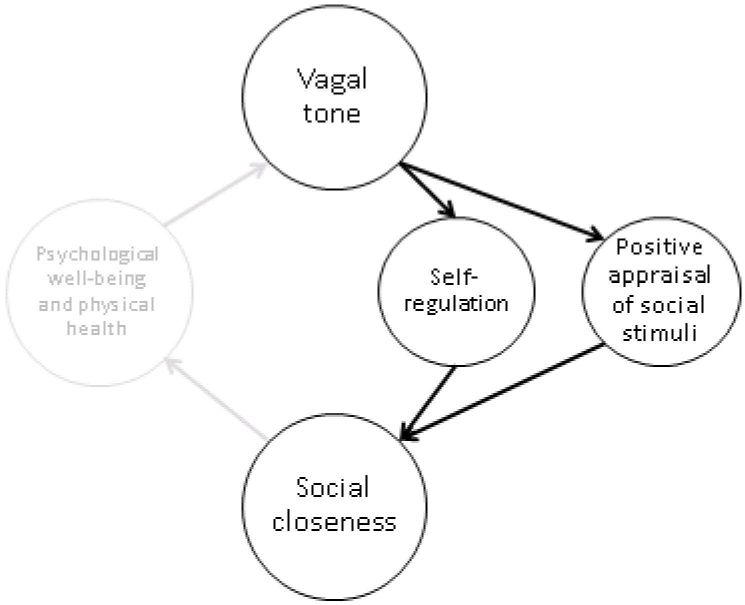
Vagal tone
Self-regulation
Positive appraisal of social stimuli
Psychological well-being and physical health
Social closeness

Figure 3.1

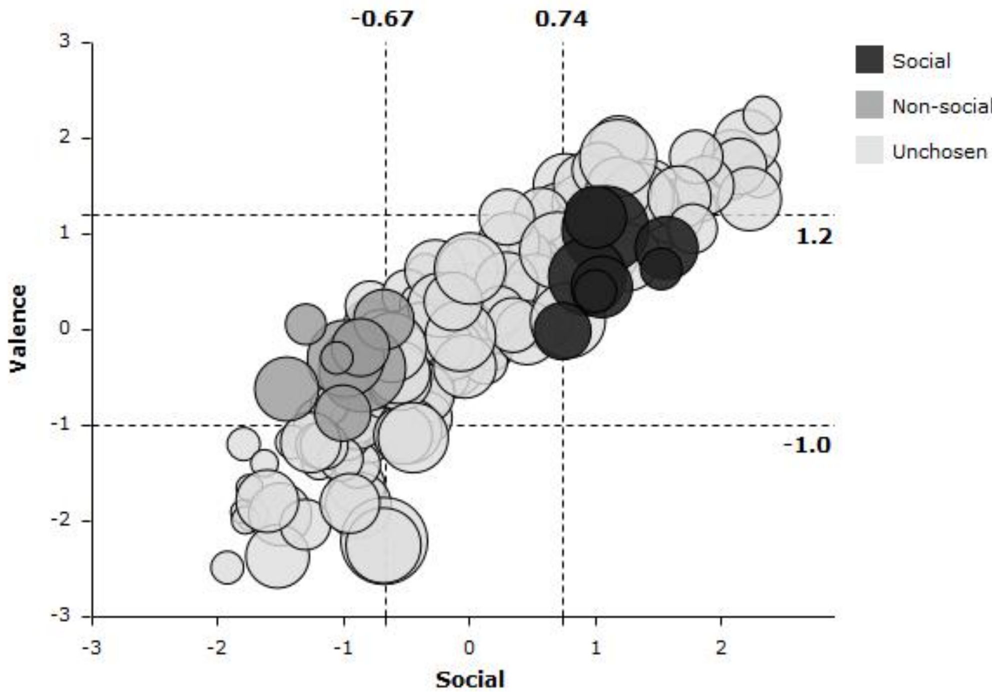
-0.67
0.74
Social
Non-social
Unchosen
1.2
-1.0
Valence
Social
3
2
1
0
-1
-2
-3
-3
-2
-1
0
1
2

Figure 3.2

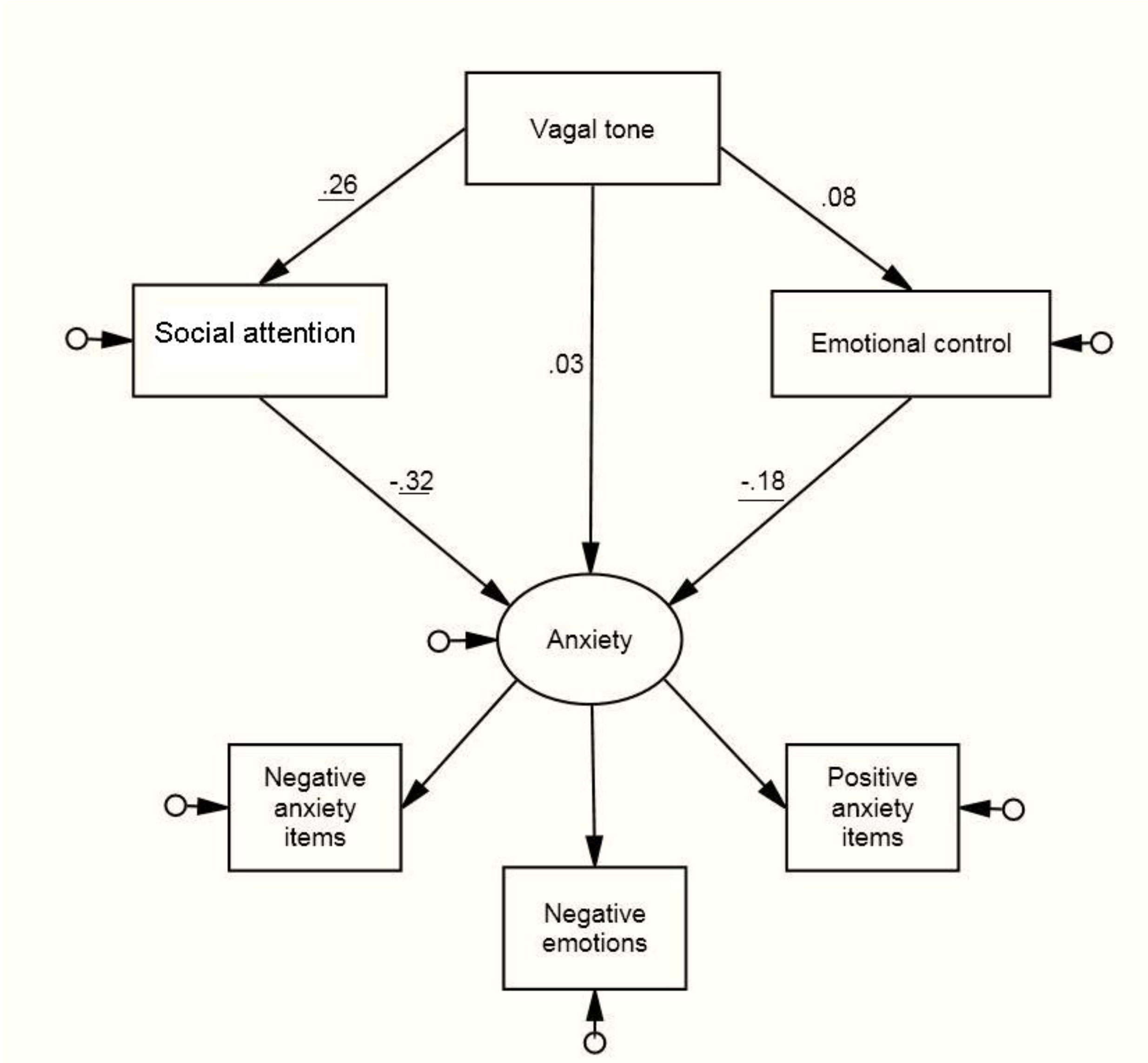
Vagal tone
.26
.08
Social attention
.03
Emotional control
-.32
-.18
Anxiety
Negative anxiety items
Positive anxiety items
Negative emotions

Figure 3.3

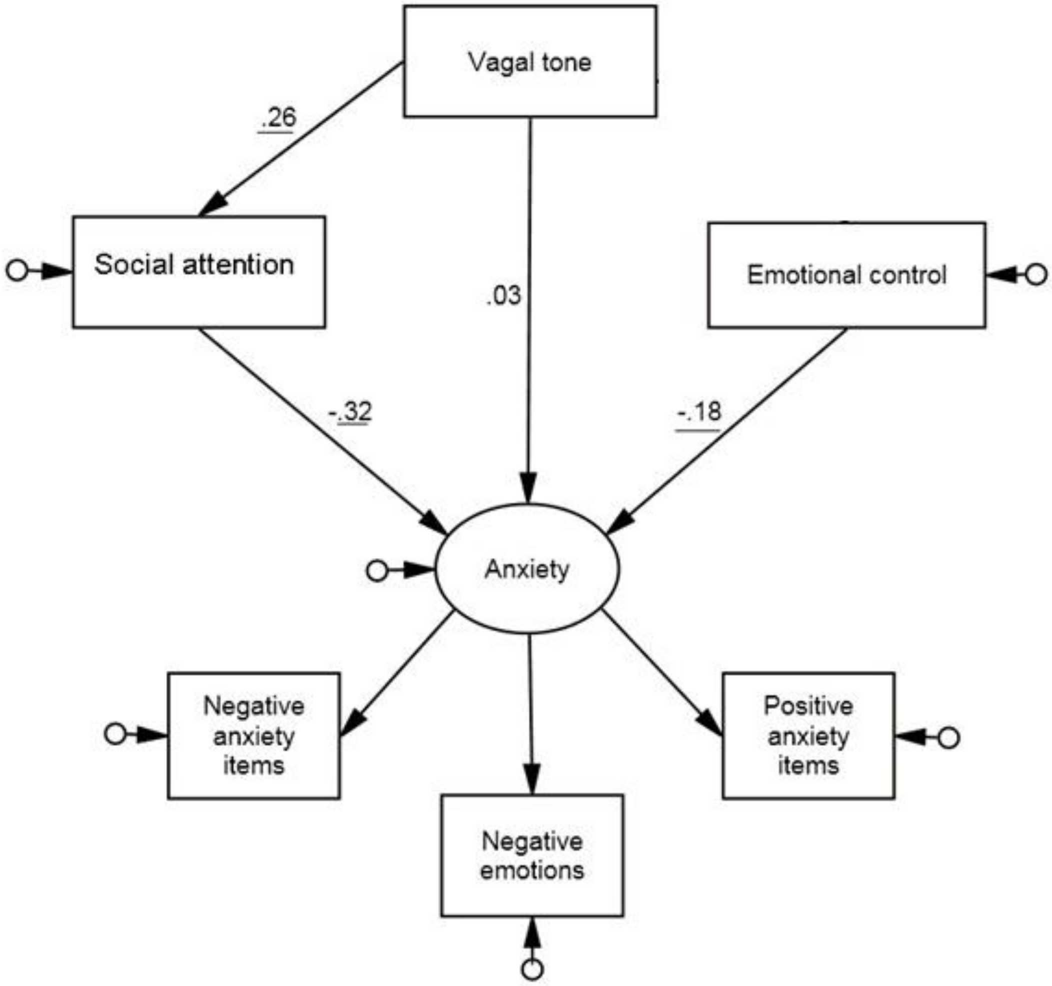
Vagal tone
.26
Social attention
.03
Emotional control
-.32
-.18
Anxiety
Negative anxiety items
Positive anxiety items
Negative emotions

Figure 3.4

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