SEEKING AND SPEAKING FROM THE HEART: INFLUENCES OF RESPIRATORY SINUS ARRHYTHMIA ON FACIAL MIMICRY AND EXPRESSED COMPASSION

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A dissertation submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Psychology and Neuroscience.

Chapel Hill
2017

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ABSTRACT

Suzannah F. Isgett: Seeking and Speaking from the Heart: Influences of Respiratory Sinus Arrhythmia on Facial Mimicry and Expressed Compassion
(Under the direction of Barbara L. Fredrickson)

Humans engage in affiliative, nonverbal behaviors, but the extent to which they do depends on context and individual indices of cardiac vagal activity (measured as respiratory sinus arrhythmia or RSA). RSA has been associated with many prosocial outcomes, yet few studies have actually examined its relationship with nonverbal behaviors. In Study 1, a sample of undergraduates (N = 75) viewed blocks of emotional faces (happy or sad) after a resting period, after a threat induction, and after a safety induction. Physiological measures and facial electromyography of the *zygomaticus major, orbicularis oculi,* and *corrugator supercilii* muscles were recorded. Analyses revealed that, under perceived threat, facial mimicry was enhanced, and this relationship depended on tonic RSA, such that higher tonic RSA significantly predicted relatively greater increases in facial mimicry under perceived threat. In Study 2, I sought to determine whether and to what extent measures of tonic *and* phasic RSA were associated with prosodic and linguistic cues of expressed compassion. A sample of 85 undergraduate participants provided baseline recordings and engaged in two tasks that elicited differentiable changes in RSA: a visual attention task to elicit vagal withdrawal, and a guided meditation to elicit vagal elevation. They then recorded two messages (expressed compassion and control) to a person in their lives who was suffering. To evaluate the effectiveness of expressed compassion, I subjected recordings to acoustic analysis, obtained listener ratings of perceived compassion from content-filtered speech, and analyzed the word content of messages. Results suggested that greater baseline RSA was associated with heightened prosodic cues of compassion (i.e., speaking more quietly), but that greater vagal withdrawal was associated with dampened prosodic cues, diminished listener-rated compassion, and an increased likelihood of using anxiety-related words. This multi-method approach demonstrated an effective technique to reliably obtain context-specific measures of RSA reactivity, and suggests the ways in which these indices of parasympathetic activity relate to social engagement behaviors. Overall, the present research provided evidence that indices of parasympathetic control are useful tools in understanding individuals' capacity to socially engage. Implications for relationship formation and wellbeing are discussed.

ACKNOWLEDGEMENTS

I often hear that completing a dissertation is like reaching the end of a winding path. But this metaphor doesn't capture the scraped knees, the unintended forays into murky woods, the glimmers of light and wisdom—and it certainly doesn't capture all the people along this path who pull you up or provide firm footing when you need it most. There have been so many people along the away who have helped me *seek* knowledge, and so many who helped give me a voice to *speak*. In particular, I offer heartfelt thanks to the following:

My advisor, Barbara Fredrickson. Thank you for taking a chance on me. I still remember the fortuitous day that I introduced myself to you (with the audacity that only undergraduates seem to possess), not yet knowing of the rewarding mentorship and intellectual paths that would follow. During my time at Carolina, you have always offered wisdom that has been a constant source of inspiration and motivation. Thank you for helping me transform my sometimes crusty, burgeoning ideas into honeypots of precision and elegance. I have become a better writer and scientist because of you.

Sara Algoe. I'm so grateful and honored to be able to call you my mentor. You have always offered a unique perspective that has challenged me and ultimately helped shape me into the researcher I am today. Thank you for your support and guidance, especially in the stages of hypothesis formation and study planning that paved the way for this dissertation.

My other committee members Katie Gates, Keely Muscatell, and Paschal Sheeran, who provided me with extremely helpful feedback and guidance. Also, a special thanks to Kristen Lindquist, who offered invaluable suggestions during my dissertation proposal.

My undergraduate advisors and mentors. Thank you especially to Jamie Williams for providing me with the tools and resources for the next stage after college, and for believing in my potential for success. Thank you to Robin Kowalski and James McCubbin for introducing me to psychological research—showing me that spreadsheets can actually be cool and uncover the intricacies of human behavior.

Ann Firestine. My goodness! I can only attempt to express how deeply grateful I am that you have been a part of my life. You are the one-and-only Lab Manager Extraordinaire; from ironing out the wrinkles of everyday existence, to providing the scaffolding upon which we build our research. I seriously cannot imagine a better lab manager. My graduate experience would not have been the same without you.

My research assistants, without whom the data presented here wouldn't exist. A special thanks to Nick Cochran, Laura Renshaw, Kristen Armel, Macey Arnold, and Alexis Hawk. All of you are brilliant individuals in your own right, and I hope that your time with me has helped you learn about the nitty-gritty process of research, as well as the resulting nuggets of understanding that eventually arise.

My fellow graduate students and peers. A warm thanks to "PEP Lab Ladies' Night" (Carrie Adair, Lahnna Catalino, Laura Kurtz, Brooke Magnus, Elise Rice, Patty Van Cappellen), in which we video chatted across three time zones! I have so looked forward to our digital hangouts this past year. Thanks for being a lovely group of pixelated shoulders to cry on. Hearing about all of your successes and past tribulations enabled me to keep trudging forward, knowing (if not always believing) that I would meet you on the other side. In addition, thanks to the other graduate students who have been so amazingly smart, funny, and tolerant: my own remaining cohort Kent Lee and Chelsea Schein, my dearest officemate Brett Major, as well as Jenna Clark, Yenping Chang, Neil Hester, Jenn MacCormack, Amelia Goranson, Holly Shablack, Heidi Vuletich, Cameron Doyle, David Findley, Jason Hannay, Khoa Le Nguyen, Aya Avishai-Yitshak, Liana Gheorma, Joshua Jackson, and Joseph Leshin.

My mom. You really are the #1 rock star of all moms ever. Thanks for being so involved and unbelievably dedicated—from helping me remember my schoolbooks *every damn day* back in third grade to reading over my cover letters today (hey, I'm not embarrassed!). I wouldn't have accomplished as much as I have if it weren't for your intense love and boundless devotion. Thank you for being my advocate, thank you for the countless sacrifices, and thank you for the emergency ponchos, both literal and figurative! Mom, you helped to get me on this "life raft," and I am so thankful that at last you can climb in beside me. I love you.

My grandmother, Nani. You have truly been like a second mother to me, and I can't thank you enough for your attention and affection. Over my whole life, I've relied on you as a constant source of love and support, from the many back rubs I probably didn't deserve, to your meticulous writing feedback and grammar tips that have most certainly made me a better writer. Thank you for being proud of me for even small accomplishments; I truly appreciate everything you have done for me.

My friends and other loved ones. Particularly my best friend Lauren Burton. Our friendship means so much to me, and I always cherish our phone calls and many laughs we share when we're together. You always know just what to say and have a true gift for being kind and compassionate; in fact, you in part inspired this research on how people speak from the heart with authenticity and love. Nikki Powell, I'm so grateful that we have kept in touch over the years. Your friendship, humor, and wit (as well as bacteria-related factoids and mutual love of animals) mean the world to me! Greg, thanks for the warm, nutritious meals, impromptu talk sessions, and taking such tender care of little man Ernie. To the rest of my family, I'm so grateful to be close to some of you and share our love of knowledge at family gatherings (as an only child, some of you are as close to siblings as I get!). I'm also filled to the brim with love for like-minded irreverent folks I consider "my people" like Amelia Abbott-Frey, Manu Raghavan, and Mark Rossi.

My partner, Anders. So glad I swiped right on you! In you I have found a fiercely loyal partner who has given me the balance needed to walk on this tenuous path. Your constancy has helped buoy me in the turbulent seas of graduate school and long distance relationships. You have cooked for me, laughed with me, cried with me, and taught me that drinking a glass of water really does make things better sometimes. Even with 500 miles between us and big milestones ahead of us, you have had faith in me and in us along the way. Thank you for your love and for making it all worth it.

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CHAPTER 1: INTRODUCTION

Imagine an individual sitting in a subway car, being whisked underground from one destination in the city to another. She might be sitting down, engaged in a conversation with a friend, intermittently making eye contact and conveying her emotional support, while thumbing a quick text message to her mother. An announcement is made over the tinny loudspeaker, but she can't understand the garbled speech, so she looks at the faces around her and sees a man's brow furrow in frustration: the train must be making extra stops. Finally, the train arrives at her destination, and she and her friend share a sigh of relief. So much of her everyday experience, like many people's, is fundamentally social. From personal relationships and the information contained in a sigh or a single brow movement, to the mere existence of cities, speaks to how deeply social interaction is woven into the fabric of our daily lives.

This is no coincidence, of course. Charles Darwin, in his seminal work *The Descent of Man* (1874), suggested that the drive to affiliate and help one another was an evolved trait:

> "Animals endowed with the social instincts take pleasure in one another's company, warn one another of danger, defend and aid one another in many ways… As [these instincts] are highly beneficial to the species, they have in all probability been acquired through natural selection." (Darwin, 1874)

Indeed, a vast body of literature from evolutionary biology (see Trivers, 1971) and psychology (for reviews, see Brown & Brown, 2006; Goetz, Keltner, & Simon-Thomas, 2010) supports this claim: many animal species, humans included, have evolved behaviors that benefit others at a cost (or at least no direct benefit) to the individual. The theory of evolution by natural selection suggests that these affiliative and prosocial behaviors, taken at the population level, promoted the survival of the species as a whole. Thus, the medium through which these social affiliative behaviors became fundamental to human nature is the same as every other evolved biological trait: the reorganization and proliferation of information—transcribed as a deceptively simple genetic code within every individual. Accordingly, biological mechanisms necessarily undergird all evolved behavior, including the affiliative behaviors that have contributed to the survival and enormous success of the human species.

Because humans have evolved to live in groups (Brown & Brown, 2006), the ability to form social bonds is a necessary precondition for successful coexistence. Social relationships are so critical, in fact, that they exert a powerful influence on health. Perceived social connection is a critical factor not only for protecting people from mental illnesses like depression (Rozanski, Blumenthal, & Kaplan, 1999), but also for buffering against physical ailments, such as chronic systemic inflammation (Cole et al., 2007), which itself can contribute to cardiovascular disease and certain types of cancers. Moreover, a meta-analysis of 148 studies on mortality found that perceived social integration was a more powerful predictor of decreasing mortality risk than other well-established health factors such as BMI, physical activity, excessive alcohol consumption, or smoking cessation (Holt-Lunstad, Smith, & Layton, 2010). In short, people need positive social connections to maintain health and wellbeing. Although it is evident that positive social relationships contribute to overall better physical and psychological functioning, the specific biological mechanisms that support our ability to connect with others are still not entirely understood. With a few notable exceptions, especially in the oxytocin literature (e.g., Taylor, 2012; for a review on oxytocin's prosocial effects, see MacDonald & MacDonald, 2010) the majority of research that addresses the biological mechanisms of human social connection focuses on *impairments* in social functioning, spotlighting disorders like autism, social anxiety, or depression. Of course, understanding how biological dysregulation is related to impaired social connection is important for tailoring interventions or future therapies. Clinical applications notwithstanding, identifying the biological underpinnings that *optimize* social connection can contribute to the scientific and medical understanding of how social relationships influence health and wellbeing.

Parasympathetic Activity: Form and Function

One candidate biological system that may function to optimize social connections is parasympathetic activity, often conceptualized as the functioning of the vagus nerve and frequently measured as respiratory sinus arrhythmia (RSA) or high-frequency heart rate variability (HF-HRV). The longest autonomic nerve in the human body, the vagus contributes to the innervation of the viscera, including the heart. Measures of cardiac vagal function like RSA have been used as a proxy for the parasympathetic nervous system's ability to offset the effects of the sympathetic nervous system to maintain growth and restorative functions (a "vagal brake"; Porges, 2007). For example, in neonates—a developmental period when growth functions are most critical—high-risk newborns exhibit reduced RSA relative to their healthy counterparts (Fox & Porges, 1985).

Vagal nerve fibers that originate from the *nucleus ambiguus* in the medulla project to the sinoatrial node ("pacemaker") of the heart and exert partial control on heart rate. Although heart rate is under the influence of several different nerves, the vagus is partly responsible for the variability in heart rate associated with respiration. This respiratory sinus arrhythmia (RSA) is characterized by a slowing of the heart rate during exhalation and an increase in heart rate during inhalation. Vagal influence on heart rate variability has been quantified in a multitude of ways. One of these methods, spectral analysis, utilizes a Fourier-transform equation to decompose the heart period waveform into power bands that correspond to frequencies. Specifically, the high-frequency power band (HF-HRV) corresponds to the frequency range of .15 to .40 Hz, and is thought to reflect variability in heart rate due to respiration, as well as the influence of the vagus nerve (Berntson et al., 1997). Another common technique to obtain vagally-influenced heart rate variability is a peak-to-valley procedure, which uses both heart rate and respiratory data to derive a measure of RSA (Grossman, 1983). While it is not currently feasible to quantify global parasympathetic activity, RSA is a relatively easy, non-invasive measure of parasympathetic control of the heart.

Beyond its purely homeostatic function, theorists have proposed that cardiac vagal activity is involved in individuals' ability to downregulate sympathetic activity and orient toward positive social stimuli (Berntson et al., 1994; Geisler, Kubiak, Siewart, & Weber, 2013), responses relevant to building and maintaining positive social relationships (e.g., Jones, Hobbs, & Hockenbury, 1982; Levenson & Gottman, 1985). Furthermore, tonic indices of cardiac vagal activity (i.e., cardiac vagal tone, or CVT) appear to be linked to positive social outcomes. Measures of CVT are associated with greater positive emotions and feelings of social connectedness (Oveis et al., 2009; Kok & Fredrickson, 2010), greater positive emotions *within* social contexts (Isgett et al., 2017), prosocial behavior (in boys, Eisenberg et al., 1995), and more supportive friend networks (Holt-Lunstad, Uchino, Smith, & Hicks, 2007). In addition, measures of CVT are related to greater social approach behaviors, such as the probability of being with others during everyday events (Isgett et al., 2017). Moreover, people with higher RSA pay greater attention to faces (Park, Van Bavel, Vasey, Egan, & Thayer, 2012), exhibit greater emotional recognition (Quintana, Guastella, Outhred, & Kemp, 2012), are more likely to seek social support as a coping mechanism (Geisler et al., 2013), feel greater affiliation toward new groups (Sahdra, Ciarrochi, & Parker, 2015), and are more likely be approach-oriented towards a novel culture (Doucerain, Deschênes, Aubé, & Gouin, 2016). Cardiac vagal tone may also serve as a physiological buffer, enabling more adaptive emotional regulation (Di Simplicio, Costoloni, Western, & Harmer, 2012; Geisler et al., 2013) and insulating people from the effects of negative social interactions, as higher tonic RSA is associated with childhood resilience to parental conflict (for a review, see Whitson and El-Sheikh, 2003).

Theoretical Understanding: Social Functions of Parasympathetic Activity

Much of the theorizing on the social functions of parasympathetic activity stems from the polyvagal theory. First posited by Steve Porges (2001; 2007; 2011), the polyvagal theory, in part, attempts to provide a neurobiological explanation for the conditions under which social engagement behaviors are likely to occur. The theory proposes that the more recently evolved portion of the vagus nerve (i.e., the myelinated vagus) co-opted the phylogenetically-ancient vagal immobilization response (e.g., threat-related freezing and death-feigning behaviors) to create an "immobilization *without* fear" response—the calm, still state that is optimal for breastfeeding, reproduction, and the formation of social bonds between infant and caregiver (Porges, 2011). From this original caretaking context, Porges (2011) suggested that other caretaking and social engagement behaviors arose in humans, from self-soothing to the formation of social bonds with romantic partners, friends, or family members.

Thus, the proper context is important for these social engagement behaviors to occur. According to the polyvagal theory, when an individual perceives an environment to be safe, the myelinated portion of the vagus nerve exerts greater control over the heart and other muscles (e.g., the striated muscles of the face, the muscles of the larynx and pharynx). Only then is the individual able to enter the "immobilization without fear" physiological state necessary for social engagement (Porges, 2011). Otherwise, neural systems that support mobilization behaviors (i.e., the sympathetic nervous system) will override this neural precondition for social connection. In other words, the human brain and body work together to continually adapt to the environment in terms of perceived threat or safety.

Furthermore, Porges proposed that "the preamble to a social bond" (2011, p. 14) is a vagally-influenced social engagement *system*—a set of neural systems (i.e., corticobulbar pathways) that facilitate certain behaviors, such as eye contact, vocalizations, facial expressions, and attuning the ear to the human voice. Several anatomical features have been called out as members of this social engagement system. Specific to the current investigations, facial muscles (for emotional expression) and laryngeal/pharyngeal muscles (for vocalizations) are examples of anatomical structures that humans use everyday to effectively communicate and socially engage with others.

According to Porges (2011) the linkage between neural regulation of the heart and the striated muscles of the face forms a "face-heart connection," which lies at the core of the social engagement system. Indeed, this relationship between vagal functioning and facial expressivity has been observed in infants (Stifter, Fox, & Porges, 1989), such that greater resting RSA was associated with greater emotional facial expressivity. In the clinical literature, there is evidence that reduced empathy-related facial expressivity is concomitant with reduced RSA in boys with behavioral disorders (Marsh, Beauchaine, & Williams, 2008). Additionally, facial expressivity is reduced in adults with major depressive disorder (Gehricke & Shapiro, 2000), which itself has been associated with reduced RSA (Carney et al., 2001).

Furthermore, the laryngeal and pharyngeal muscles are necessary for producing vocalizations and speech. A small body of evidence has directly implicated vagal function in vocal prosody—qualities of vocalizations such as pitch, loudness, and rhythm. In one study, a reduction in vagal activity was associated with higher-pitched cries in infants undergoing circumcision (Porter, Porges, & Marshall, 1988). Another study linked phasic shifts in vagal activity (i.e., decreases in RSA, known as vagal withdrawal) to overall higher pitch and less pitch variability in infant vocalizations during a stressor; however, tonic RSA was not associated with any differences in prosody (Stewart et al., 2013). This small body of work suggests that high-frequency, more monotonic vocalizations (at least during stress) are associated with lower vagal activity, which corroborates the finding that depressed adults have reduced prosody (Garcia-Toro, Talavera, Saiz-Ruiz, & Gonzalez, 2000) and reduced cardiac vagal tone (e.g. Agelink et al., 2004; but see Rottenberg, Wilhelm, Gross & Gotlib, 2002). Conversely, this work suggests that increases in vagal activity may be associated with lower-frequency, more prosodic vocalizations (i.e. greater pitch variance and pitch range), although it is not clear under which conditions this pattern would be evident.

Behavioral Link to the Polyvagal Theory: Study 1, Facial Mimicry

Given that the "face-heart connection" articulated in the polyvagal theory is at the core of the social engagement system, facial expression is a natural behavioral target to extend empirical work to test this theoretical tenet. The perception of others' emotions, attitudes, desires, or bodily states through the contortion of facial musculature is an evolved ability that humans share with other primates (for a review, see Haxby, Hoffman, & Gobbini, 2000). There exist brain regions and distributed networks that are specialized to process faces (Haxby, Hoffman, & Gobbini, 2000), and the recognition of facial information can even be observed at the level of a single neuron (Quiroga, Reddy, Koch, & Fried, 2005). Facial expression of emotion is considered by many scholars to be universal (for a review, see Russell, 1994), although whether or not there are a set of discrete universal emotions is hotly debated (see Ekman, 1993; Lindquist, Wager, Kober, Bliss-Moreau, & Feldman Barrett, 2012). Regardless of theoretical perspective, it is not contested that facial expressions are integral to everyday life.

Aside from mere perception of faces, muscle movements in the face may play a distinct role in empathy and perspective-taking (Stel & van Knippenberg, 2008). Humans automatically mimic the emotional expressions of others; that is, their facial muscles imitate a person (sometimes imperceptibly to the naked eye) with whom they are interacting (Hess, Philippot, & Blairy, 1998). Indeed, mimicry may be one of the first steps in forming and maintaining a social relationship. For example, when a person smiles, part of the way another person understands the meaning of this facial expression is through mimicking the facial muscle movements that create that expression (Neal & Chartrand, 2011). While facial mimicry is not always crucial for the mere recognition of an emotional expression (Hess, Philippot, & Blairy, 1998), the simulation of facial expressions is important in aiding our understanding of others' subtle mental states, and attuning our behavior accordingly (Niedenthal, Mermillod, Maringer, & Hess, 2010). A related phenomenon, behavioral mimicry (which is not specific to the face), is associated with higher quality social interactions (Stel & Vonk, 2010), assists in building rapport (Lakin & Chartrand, 2003), and strengthens social bonds (Lakin, Jefferis, Cheng, & Chartrand, 2003). Moreover, individual differences in perspective-taking ability (Chartrand & Bargh, 1999), as well as attitudes toward the person being mimicked (Likowski, Müholberger, Seibt, Pauli, & Weyers, 2008) can moderate the degree to which people engage in mimicry (for a review, see Chartrand & Lakin, 2013).

Behavioral Link to the Polyvagal Theory: Study 2, Expressing Compassion

Behaviors that involve caretaking or soothing mirror the first social bonds that humans form between caretaker and infant, which are implicated in social engagement under the polyvagal theory. Furthermore, *increased* vagal activity is theoretically a precondition for these behaviors to occur. In particular, given the link between vagal functioning and anatomical structures required for speech production, one meaningful avenue through which caretaking behaviors could be measured is through speech and vocalizations. Vocalizations, produced in part by laryngeal and pharyngeal muscles, are one of the fundamental ways humans communicate nonverbally.[1] Thus, it follows that measures of cardiac vagal activity might modulate the extent to which individuals effectively communicate with others, as measured by prosody, listeners' subjective perceptions, or linguistic content of an emotional expression.

Expressing emotion through the voice. The acoustics of speech are immensely important in communicating subtleties of meaning that reach beyond the literal interpretation of the spoken word. Aside from language content, vocalizations also contain rich emotional information in prosody. There are a multitude of vocal acoustic properties that define prosody, such as *jitter* and *shimmer* (which relate to the quality or roughness of the voice) that may also convey different information. However, because the research relating these more complex measures to affective states is limited, the scope of the present research only focuses on the

[1] Paralinguistic qualities of speech (that is, qualities of speech that exclude linguistic content) are considered a form of nonverbal behavior.

most widely studied vocal parameters: fundamental frequency (i.e. pitch), and amplitude (i.e. intensity or loudness).

Relative to other modalities of nonverbal behavior, vocal communication has received relatively less attention in the field of affective science. Although this is not to deny the considerable body of literature on vocalizations of emotion (see a review, see Scherer, 2003), by far the most popular medium of studying emotion expression is through the face (Burgoon, Guerrero, & Floyd, 2016, p. 306). Regardless, vocal prosody not only communicates people's own affective states, but it also conveys information to regulate others' affective states. For example, parents across many cultures consistently speak to prelinguistic infants in a characteristic tone known as "motherese"; the speech acoustics of which are characterized by overall higher pitch, a more exaggerated range of pitch, and longer pauses (Fernald & Kuhl, 1987). Studies suggest that motherese is helpful in directing the infant's attention (Stern, Spieker, & MacKain, 1982) and regulating infant arousal (Fernald, Kermanschachi, & Lees, 1984).

Motherese notwithstanding, researchers have characterized the acoustic features of other emotion-laden vocalizations (Scherer, 2003). Although human listeners are fairly accurate at categorizing emotional vocalizations (e.g. Scherer, Banse, & Wallbott, 2001), researchers have not agreed upon acoustic patterns associated with discrete emotions, which suggests that, like facial expressions, interpretation of vocal emotion cues is more complex than a discrete emotion framework would suggest (Bachorowski, 1999). Nevertheless, high arousal states, such as anger, fear, or elation, are associated with an increase in the fundamental frequency (i.e., overall pitch) and amplitude (i.e., intensity or loudness), while low arousal states are generally associated with a decrease in pitch and intensity. For example, in a multitude of studies summarized by Juslin and Laukka (2003), both sadness and tenderness (love) were characterized by lower voice intensity and variability (i.e., speaking more quietly with less variability in loudness), as well as lower pitch mean and variability. In clinical settings, one study found that during an "empty-chair" exercise, in which participants verbalized negative feelings to someone who was not physically present, voice pitch increased—concomitant with increases in fear and anxiety—compared to a reframing condition (Diamond, Rochman, & Amir, 2010). In a study of therapist-patient interactions, higher empathy was significantly correlated with the therapist speaking at a lower pitch, and these higher-empathy sessions also exhibited greater vocal synchrony between therapist and patient (Imel et al., 2014). Thus, vocal acoustics may serve as a cue that aids in the effective communication of empathic concern, and may even be another component of biobehavioral synchrony, in which two or more individuals' changes in behavior (e.g., movement, speech rate) and biology (e.g., cardiovascular activity) become time-locked as they interact (a definition proposed by Feldman, 2012).

Function of language. Although vocalizations are critical to the expression of emotion through speech, they do not capture another component of emotional speech: language. Language is the most readily observable medium through which humans communicate, and some scholars believe it plays a pivotal role in constructing the experience of emotion (see Lindquist, Barrett, Bliss-Moreau, & Russell, 2006). Considerable research has explored the psychological functions of language (Chung & Pennebaker, 2007), and even how language relates to human health and wellbeing. For instance, an early study of health and language found that that the frequency of self-references ("I" pronouns) was associated with higher blood pressure for people at risk for coronary heart disease (Scherwitz, Berton, & Leventhal, 1978), and self-references have also been associated with greater indices of depression (Rude, Gortner, & Pennebaker, 2004; Stirman & Pennebaker, 2001). Conversely, greater use of non-I pronouns—that is, relatively more focus on others than the self in speech or writing—is associated with greater health outcomes (Chung & Pennebaker, 2007) and less cardiovascular arousal during conflict discussion (Seider, Hirschberger, Nelson, & Levenson, 2009). Thus, language may serve as in important marker of underlying psychological processes that impinge on social relationships. The relationship between vagal activity and language—despite their overlap in psychosocial processes—is a heretofore unexplored avenue of research (but see Seider et al., 2009, for the relation between overall cardiovascular activity and language use).

Vagal Flexibility: Sensitivity to Context

Measures of cardiac vagal tone (CVT) are typically recorded when the participant is at rest—alone with his or her own thoughts. Thus, it is possible that, while RSA purportedly measures the strength of a person's vagal brake, it cannot assess how flexibly the person is able to engage or withdraw the vagal brake in appropriate contexts. Whereas the influence of the myelinated vagus nerve helps lay the physiological groundwork necessary for social engagement, humans must also be vigilant to their ever-changing environment. Just as ego-resiliency has been conceptualized as a person's "ability to equilibrate and reequilibrate in response to their ever-changing being and ever-changing world" (Block & Kremen, 1996, p. 349), vagal activity may serve as a biological analog. The vagus nerve must exert its influence in a context-dependent manner, and individuals vary in the degree to which they possess this "vagal flexibility," a term coined by Muhtadie, Koslov, Akinola, and Mendes (2015). For instance, it is not always adaptive to have an "immobilization without fear" response. As a clinical example, children with Williams Syndrome, a genetic disorder caused by a hemideletion on chromosome 7, could be considered to have an overactive social engagement system, one that is not sensitive to context. These children are abnormally drawn to social stimuli, have heightened vocal prosody, and show social disinhibition (Kaplan, Wang, & Francke, 2001). Although no data, to my knowledge, relate cardiac vagal functioning to Williams Syndrome, children with this disorder show greater heart rate deceleration (indicative of greater orientation toward a stimulus), in response to emotional faces, indicating high approachability to social stimuli, regardless of the emotional valence of faces (Skwerer et al., 2009). Despite their hypersociability and cheerful demeanors, these children frequently experience social rejection because of their apparent lack of attention to subtle social cues (for a review, see Kaplan, Wang, & Francke, 2001). Thus, children with Williams Syndrome may serve as a powerful illustration of the importance of exquisite attunement to ever-changing *social contexts* (Block & Kremen, 1996; Muhtadie et al., 2015) in the successful formation of social connections.

Therefore, phasic measures of vagal flexibility—not just indices of cardiac vagal tone obtained at rest—may be more predictive of social affiliative behaviors in *appropriate* contexts. In a series of studies that tested the construct of vagal flexibility—defined as greater decreases in RSA during attentional demand—the authors (Muhtadie et al., 2015) assessed RSA at a resting baseline and during an attention-demanding task that reliably elicited vagal withdrawal. Their individual difference measure of vagal flexibility—which included both resting RSA and task-related change in RSA as independent variables in regression analyses—predicted greater emotional accuracy and sensitivity to both positive and negative social feedback. Specifically, individuals who had greater vagal flexibility self-reported greater shame and exhibited higher blood pressure after receiving negative feedback, but less self-reported shame and lower blood pressure after receiving positive feedback. The same analyses, using resting RSA alone (without the addition of vagal flexibility) were not predictive of emotional accuracy or sensitivity to positive and negative feedback. Thus, vagal flexibility seems to have unique power in predicting social outcomes that are dependent on sensitivity to the social environment.

However, Muhtadie and colleagues' conceptualization of vagal flexibility is limited to a baseline-versus-challenge framework; that is, vagal flexibility is only defined as context-dependent vagal *withdrawal*, controlling for tonic measures of vagal function (i.e., resting RSA). In other words, the study did not expand the framework of vagal flexibility to include changes in vagal activity in the opposite, positive direction. A more comprehensive definition of vagal flexibility would encompass both context-appropriate decreases *and* increases in vagal activity.

Vagal Elevation: Propensity for Social Engagement

If vagal withdrawal (in response to a challenge task) is more predictive of certain social outcomes than cardiac vagal tone alone, it is possible that context-appropriate increases in vagal activity—a concept I term "vagal elevation"—may also have unique, predictive power in the social domain. To date, no studies have explicitly studied vagal elevation as a physiological marker of the capacity for social engagement (but see Bornemann, Kok, Böckler, & Singer, 2016). However, many empirical studies report the conditions under which vagal activity increases. Vagal activity increases during mindfulness body scans (Ditto, Eclache, & Goldman, 2006; Krygier et al., 2013), the emotional experience of compassion (Stellar, Cohen, Oveis, & Keltner, 2015), and downregulation of negative emotions like disgust and distress (Butler, Wilhelm, & Gross, 2006; Oppenheimer, Measelle, Laurent, & Ablow, 2013). Taken together, these findings indicate that vagal elevation seems to occur in contexts that may be construed as caretaking behaviors: whether it is through self-soothing, such as mindfulness body scans and emotional regulation, or through expressions of compassion, an other-focused emotion that promotes caretaking behaviors in difficult or distressing circumstances (Eisenberg & Miller, 1987). If this is the case, it is possible that the degree to which people's vagal activity increases in such contexts (i.e., vagal elevation) is a physiological marker for the propensity for social engagement.

Furthermore, I propose to delineate the concept of vagal elevation from cardiac vagal tone in both its definition and function. This is because cardiac vagal tone, a baseline measure of parasympathetic activity, is typically gathered while an individual is in relatively confined solitude for several minutes and may not be the most ecologically valid measure of the propensity for social engagement. That is, although CVT may be a measure of the strength of the "vagal brake," it is not measuring the vagal brake *in action*. A measure of vagal activity within contexts in which it is expected to increase (i.e. vagal elevation) may be a more valid and predictive physiological marker of the propensity for social engagement.

To this aim, I propose that the newly minted term "vagal flexibility" (Muhtadie, Koslov, Akinola, & Mendes, 2015) be expanded to include all context-appropriate changes in vagal activity: a) vagal withdrawal to meet the greater metabolic demands of challenging situations, and b) vagal elevation to allow growth, restorative, and affiliative functions to take precedent in safe contexts. I propose that, while flexible employment of vagal withdrawal is associated with social sensitivity (i.e., greater attunement to social information), flexible employment of vagal elevation may be associated with greater capacity for social engagement (i.e., greater ability to engage in social behaviors with others).

Summary and Overview

In the research reviewed above, I discussed the need for empirical testing of the polyvagal theory in the domain of social behaviors, as well as the inclusion of more ecologically-valid physiological markers of the propensity for social engagement. First, in Study 1, I aimed to test the premise that in the context of perceived threat or perceived safety, an individual's tonic levels of cardiac vagal activity (measured as resting RSA) will moderate the degree to which individuals engage in automatic affiliative behavior. Specifically, I measured the electrical activity present in facial muscles (via facial electromyography or EMG) to quantify the degree to which people engaged in facial mimicry. Then, I tested whether and to what extent resting RSA influenced changes in facial mimicry in a context of threat or a context of safety. In Study 2, I shifted the focus from how measures of cardiac vagal tone modulate behavior in different contexts, to instead explore how different contexts *change* measures of cardiac vagal activity, and whether these changes uniquely predict affiliative behaviors. Specifically, I measured RSA in contexts linked—in theory and past research—to vagal withdrawal (phasic decreases in RSA) and vagal elevation (phasic increases in RSA), respectively. Then, I had participants record spoken messages to a suffering relationship partner, and I quantified these vocal expressions of compassion by analyzing their objective acoustic properties, subjective listener-perceptions, and linguistic content. I tested whether and to what extent cardiac vagal activity in different contexts (i.e., resting RSA, vagal withdrawal, vagal elevation) predicted properties of these messages.

CHAPTER 2: STUDY 1

My overarching aim for this study was to investigate whether and when cardiac vagal tone plays a role in translating the dispositional tendency to seek social interaction into automatic affiliative behaviors. Thus, for this investigation I sought to target behaviors that are theoretically tied to the social engagement system—in this case spontaneous facial mimicry. To my knowledge, facial mimicry has not previously been tested in the context of the polyvagal theory, although several studies in clinical populations have examined the relationship between autonomic function and facial EMG (e.g., in boys with behavioral disorders; Marsh, Beauchaine, & Williams, 2009; de Wied, van Boxtel, Matthys, & Meeus, 2012). Because of the key role that facial expressions play in the enacted social engagement system, the aim of this study was to test whether and under what conditions cardiac vagal activity predicted facial mimicry.

Furthermore, because the polyvagal theory directly implicates perceived safety (vs. perceived threat) as openness to (vs. avoidance of) social bonding, I was interested in how these automatic affiliative behaviors change under perceived safety or threat, and whether cardiac vagal tone can explain variability in any such changes. Porges purports that perceived safety downregulates defensive neural networks, enabling social engagement behaviors to occur (2011, p. 58). Thus, I predicted that a state of safety would enhance affiliative behaviors. By contrast, Porges suggests that a state of perceived threat allows "physiological states that support fight, flight, or freeze behaviors, but not social engagement behaviors," and that social engagement occurs "only when these defensive circuits are inhibited" (2011, p. 58). However, this prediction—that a state of perceived threat is non-conducive to social engagement—contradicts a large body of evidence from the psychological literature that threat (or stress) actually *enhances* affiliative behavior. This literature builds partly on early work showing that impending threat increases affiliation behavior (e.g., Schachter, 1959; Darley & Aronson, 1966; Buck & Parke, 1972). Furthermore, in the social exclusion domain—which is a social form of threat—much evidence suggests that humans behave in ways that indicate greater motivation to affiliate with others (Maner, DeWall, Schaller, & Baumeister, 2007; cf. Twenge & Campbell, 2003). In some cases, this affiliative behavior has been observed in the form of behavioral mimicry (Lakin, Chartrand, & Arkin, 2008). This evidence for social affiliation under threat would lead to the hypothesis that—in nonclinical samples of adult humans—perceived threat would increase affiliative behaviors. Regardless, because parasympathetic activity plays a role in supporting social relationships more generally, it is reasonable to suspect that people with higher cardiac vagal tone would show relatively more automatic facial mimicry under perceived safety *and* under perceived threat, compared to people with lower cardiac vagal tone. However, to be consistent with the polyvagal framework while also considering conflicting evidence from other sources, I leave open the possibility that under a state of physiological threat, there may be a main effect of enhanced *or* inhibited facial mimicry. Taken altogether, my research aimed to test the following three hypotheses, with one set of competing hypotheses:

Hypothesis 1. Under no external perceptions of safety or threat, higher levels of resting RSA predict greater levels of automatic facial mimicry.

Hypothesis 2. Under perceived safety, resting RSA moderates the change in automatic facial mimicry, such that people with higher RSA exhibit relatively more facial mimicry.

Hypothesis 3. Under perceived threat, resting RSA moderates the change in automatic facial mimicry, such that:

A. Overall people mimic *less* under threat, but that this effect is *attenuated* for people with higher RSA.
B. Overall people mimic *more* under threat, and this effect is *enhanced* for people with higher RSA.

Overview of Empirical Strategy

The study implemented a 3-level (Control, Safety, Threat) within-participants design that took place in a one-hour laboratory session. The primary predictor, resting RSA, was first obtained before participants viewed three blocks of faces (one for each condition). The Control condition was always presented first to prevent potential carryover effects from the experimental blocks. Then, a state of safety or threat was induced for the Safety or Threat conditions, respectively; in each case, participants listened to several minutes of sound stimuli pre-rated to be either safe/calming or threatening. The order of the Safety and Threat conditions was counterbalanced among participants. After each sound set, a block of faces was presented. Physiology (cardiovascular measures, respiration, and facial electromyography) was recorded concurrently.

Method

Participants

Ninety-five undergraduate students (73% female; M_{age} = 18.84, *SD* = 0.99) in an introductory psychology course at the University of North Carolina at Chapel Hill completed a study called "Memory for Faces" for course credit. Sixty participants self-identified as

Caucasian, 15 as African-American, 11 as Asian, 2 as American Indian, and 5 as more than one race. Eight participants self-identified as Hispanic or Latino.

Measures

Cardiovascular activity and respiration. An electrocardiogram (ECG) was obtained to measure heart rate. Disposable electrodes were placed in a bipolar configuration on the lower ribs, on opposite sides of the torso; a ground electrode was placed on the top of the hand. To measure finger pulse amplitude and transit time, a plethysmograph sensor was attached to the middle finger of the non-dominant hand. Respiration rate and amplitude were collected with a pneumatic bellows, which was placed at the bottom of the sternum, encircling the participant's torso.

Respiratory sinus arrhythmia (RSA). Raw recordings of heart rate were preprocessed and manually edited to correct for artifacts. Custom software by James Long Company (Caroga Lake, NY, USA) was used to calculate RSA, employing a modified Grossman peak-to-valley method with resampling every 125 ms (Grossman, 1983). Resting RSA was calculated for resting assessments and during sound stimuli. Physiology was measured continuously at a sampling rate of 1000 Hz for the duration of the tasks, excluding questionnaires.

Facial electromyography (EMG). Following guidelines offered in Fridlund and Cacioppo (1986), three pairs of electrodes were placed on the right side of the face to measure facial muscle activity of the *corrugator supercilii* (CS)*,* the *orbicularis oculi* (OO) and the *zygomaticus major* (ZM). To measure CS activity, one electrode was placed directly above the medial corner of the eyebrow and the other 1 cm lateral to the first, along the brow line. To measure OO activity, one electrode was placed approximately 1 cm inferior to the outermost corner of the eye and the other 1 cm medial from the first, following the curve of the eye socket.

The third set of electrodes measured ZM activity: a pair of electrodes was placed midway between the corner of the mouth and the preauricular depression of the ear.

Tin cup electrodes (ECI, Eaton, OH, USA) with adhesive collars were filled with electrical conducting gel (Electro-Gel, ECI, Eaton, OH, USA) before placement. Then, a cotton swab with an abrasive cleaning gel (NuPrep Skin Prep Gel, Weaver & Co., Aurora, CO, USA) was used on each muscle site to remove dirt, makeup, or oil from the skin. Medical tape was applied to electrode sites, and hair clips were used to pin wires to the head or shirt for greater stability. Electrical impedance for each electrode pair was tested with an impedance meter (Checktrode 1089 MkIII, Morro Bay, CA, USA), and electrodes were reapplied if impedance was above 40 kΩ.[2] Once collected, EMG data were first band-pass filtered (90 – 250 Hz), and then rectified over 100-ms windows. For a given face stimulus (3600 ms), EMG signal was calculated as the mean voltage across all 100-ms windows.

Pre-stimuli resting assessments. For the initial resting assessment, which lasted 2.5 minutes, participants were instructed to sit quietly for several minutes and "not to think about anything in particular, just relax." Immediately afterward for the second assessment, which also lasted 2.5 minutes, they viewed a slideshow containing twenty neutral images from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2008), with each image presented for 7.5 seconds.

Face viewing task. One block of faces was presented for each of the three conditions: Control, Safety, and Threat. For each block, twelve unique faces were presented, which comprised six happy and six sad expressions, in pseudorandom order. Stimuli were dynamic facial expressions; the expresser's face was first neutral, then gradually morphed into an

[2]Most impedance values fell below 20 kΩ. In some cases, lower impedance was not achieved. In these cases, EMG signal was inspected on-line for high levels of noise and, if necessary, marked as non-usable *a priori*.

emotional expression (happy or sad), and gradually morphed back to the neutral expression. Each stimulus lasted for 3600 ms, with apex expression culminating at 866 ms for a duration of 1667 ms. This timeframe from neutral to apex has been used in previous studies, and has been shown to elicit greater facial mimicry than static images (Rymarczyk, Biele, Grabowska, & Majczynski, 2011). Faces were drawn from a pool of female, male, and racially diverse expressers (for details on face stimuli, see Appendix B).

Electronic questionnaires. Participants completed several questionnaires on the computer, some of which were not included in the primary analyses. After placement of physiological sensors but before the physiological recordings began, participants responded to an affect grid and were assessed on physical activity, personality, and demographics. Towards the end of the session, after the physiological recording and face-viewing task had ended, participants responded to a second affect grid and were assessed on (in the order listed) empathic accuracy, group entitativity, attachment styles, social approach/avoidance motives, prioritizing positivity, subthreshold autistic traits, and loneliness. A description of questionnaires can be found in Appendix A.

Memory task. After the completion of the set of electronic questionnaires, participants completed a memory task that was part of the cover story. Participants were shown 16 neutral-expression faces presented in random order, and asked, "*Do you remember seeing this face?*" Participants responded either yes or no. Eight of the faces had been shown previously in the face-viewing task, and the other eight were novel faces participants had not been shown. All face stimuli were originally from the same standardized face sets.

Safety and threat induction. Two sets of audio stimuli were used to induce a state of safety (Safety condition) or state of threat (Threat condition), the order counterbalanced among participants. For both experimental conditions, the set of audio stimuli was played immediately before the face block. Each set of sounds was composed of 20 audio clips, lasting six seconds each, with one second between clips (set duration time = 139 seconds). Individual sound stimuli were selected from the International Affective Digitized Sounds database (IADS-2), which has an array of naturally occurring sounds that are pre-rated on valence, arousal, and control dimensions (Bradley & Lang, 2007). For the Safety condition, sounds were rated as having lower arousal and positive valence (e.g., children laughing, babbling brook), 10 of which were social (i.e., vocalizations present) and 10 of which were non-social. For the Threat condition, all stimuli were rated as highly arousing and negatively valenced (e.g., fist fight, dentist's drill); again, 10 were social, and 10 were non-social. The order of the individual sound stimuli within each audio set was random. In addition, prior to the study, a sample of 90 online participants recruited from Amazon Mechanical Turk (MTurk) had rated each sound set as a whole on the degree to which they were threat-inducing or safety-inducing (for details on how sound stimuli were selected and rated by the MTurk sample, see Appendix C).

Body mass index (BMI). Participants' height and weight were instrument-recorded at the end of the session to calculate BMI.

Procedure

A schematic of the study procedure is shown in Figure 1. Participants were seated in a private, sound-attenuated cubicle with a desktop computer. After providing informed consent, they were given a cover story that the researcher was interested in how auditory stimuli and physiology influence memory for faces. The examiner conveyed an overview of the study—that the participant would provide physiological recordings, view faces, listen to sounds, and be asked to recall the faces afterwards. Next, the examiner applied physiological sensors as described above, and helped place headphones on the participant, which he or she wore throughout the experiment until the post-task questionnaires. To allow time to habituate to the sensors, participants completed several questionnaires on the computer.

Next, all participants were left alone in the private cubicle without interruptions until the face viewing task ended. Participants were asked to follow instructions on the computer, which directed them through the resting assessments and the face-viewing task (described above). Thus, after the resting assessments, the computer instructed participants to view and remember the faces presented; then, the first block of faces was presented (Control condition). Next, for the Safety or Threat condition, a set of sounds (safety- or threat-inducing) was played. Immediately after, a second block of 12 faces was presented, followed by a one-minute neutral slideshow. After the slideshow, the other set of sounds was played for the Safety or Threat condition, followed by a third block of 12 faces. All stimuli were presented using E-Prime 2.0 Professional software (Psychology Software Tools, Sharpsburg, PA, USA). Event markers were sent to the acquisition computer to to mark the beginning of each neutral slideshow, sound set, and individual face presented.

After the face viewing task ended, the experimenter re-entered the cubicle, turned off the recording device, and removed the headphones and finger pulse sensor. The participant then completed a set of post-task questionnaires. The questionnaires administered are listed under "Measures" above; for a full description of all questionnaires, please see Appendix A. Once participants were finished, the experimenter disconnected all sensors and removed them from the participant's body. Finally, the participant's height and weight were instrument-recorded, and they were debriefed as to the true purpose of the electrodes; after debriefing, participants were thanked and dismissed.

Results

Preliminary Analyses

Three participants encountered procedural errors or software crashes during the study, and 11 participants had physiological data (at least one ECG or EMG channel) that were unusable or abnormal. In addition, six participants whose mean respiration rates fell outside the 0.12- to 0.40-Hz frequency band were excluded, as these more extreme respiration frequencies have been shown to distort measurements of RSA (Berntson, et al., 1997). Thus, a total of 20 participants were removed for the final analysis sample ($N = 75$).

Resting physiological assessments. Two, 2.5-minute resting assessments—one in which the participants were given no specific instructions, just to relax ("initial assessment"), and one in which participants viewed a neutral slide show ("proximal assessment")—were used in the original study design. I decided to implement both versions because although relax-only assessments are more commonly used, some researchers argue that they may be less stable and less reliable than minimally-demanding assessments (e.g., with a neutral slideshow; Jennings, Kamarck, Stewart, Eddy, & Johnson, 1992). Descriptives of physiology and differences among the initial-only, proximal-only, and combined assessments (called "resting period" throughout) are shown in Table 1. Overall, the pattern of physiological responses was different between the two types of assessments; critically, RSA was significantly higher during the initial assessment. In addition, initial assessment heart rate was significantly lower (although by < 1 beat per minute on average), and observed respiration measures suggest that participants breathed more deeply (greater tidal volume) and more slowly (longer respiration period, although by < 1 second). Differences notwithstanding, recently-published guidelines reinforce the gold standard that RSA measurement duration should last at least 5 minutes

(Berntson et al., 1997; Laborde, Mosley, & Thayer, 2017). Therefore, analyses presented here utilize the average of the two resting assessments as the index of resting RSA. For completeness, all analyses were also conducted using each of the other two resting periods. Whether or not the combined or individual resting periods were used, the overall pattern of results remains the same, and any deviations are reported here in footnotes. In the combined resting assessment, raw RSA values were positively skewed, and indices of skewness (1.99; *SE* = 0.28) and kurtosis (5.32; *SE* = 0.55) exceeded twice their standard errors. Thus, RSA values were natural log-transformed to achieve a normal distribution.[3]

Facial EMG standardization and data reduction. Due to inherent differences in the degree of EMG signal produced by different muscles sites (Larsen, Norris, & Cacioppo, 2003), and that within-individual variance tends to be different among participants, it is standard practice to transform raw EMG activity to enable comparisons across individuals. Methods to achieve this vary, although most sources agree that some form of transformation is necessary (see Fridlund & Cacioppo, 1986). Frequently, EMG activity during a stimulus is standardized to EMG activity during a baseline, by either taking the difference or deriving a percentage score (for the subtraction method, see Aguado et al., 2013; for the percentage method, see de Wied, van Boxtel, Matthys, 2012). Transforming data into *z*-scores has also been recommended for both normal and skewed EMG data (Bush, Hess, & Wolford, 1993). For this study, I followed transformation procedures used in the facial mimicry literature (*z*-transformed difference scores; e.g., Hess & Blairy, 2001), although an alternative transformation method and results can be found in Appendix D. First, within each muscle site (CS, OO, and ZM), a difference score was taken between baseline EMG activity (i.e., the five-

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[3]Instead of a log transformation, analyses were also conducted using raw RSA, as well as a square root transformation, and the pattern of results is identical.

minute period before the face viewing task) and EMG activity during a given stimulus (i.e., during each 3600 ms presentation of a face stimulus), such that higher scores indicate greater EMG activity during a stimulus. Second, difference scores were transformed into within-participant *z*-scores. Finally, the standardized difference scores were averaged across emotion type (sad and happy) for each muscle site. In all analyses for which sphericity assumptions were violated, degrees of freedom and *p*-values are reported with a Greenhouse-Geisser correction. For repeated-measures analyses, within-participant univariate test statistics are reported.

Manipulation check: Happy and sad faces. Before testing the main hypotheses, I verified that stimuli elicited a response of facial mimicry across all conditions: specifically, greater activity (i.e., greater standardized difference scores) of the *orbicularis oculi* (OO) and *zygomaticus major* (ZM) in response to happy faces, and greater activity of the *corrugator supercilii* (CS) in response to sad faces. Because EMG activity was standardized within participants, comparisons can be made among muscle sites with regard to relative increases or decreases in EMG activity for a given participant. A repeated-measures general linear model (GLM) or RM-ANOVA was used with muscle site and emotion type as within-participant factors. As predicted, there was a significant interaction between muscle site and emotion type, $F(1.458, 106.383) = 41.357$, $p < .001$. Pairwise comparisons with Bonferroni adjustment revealed that there was significantly more activity in the CS muscle during sad faces than happy faces ($p < .001$). Conversely as predicted, there was significantly more OO muscle activity during happy faces than sad faces ($p < .001$), and significantly more ZM muscle activity during happy faces than sad faces ($p < .001$). I concluded that happy and sad faces elicited patterns of facial mimicry in the predicted direction for all three muscle sites. Means of participants' facial EMG activity at each muscle site are shown in Figure 2. Zero scores equal mean EMG levels within participants (*z*-scores) and not the absence of EMG activity.

Manipulation check: Safety and threat. The Safety and Threat stimuli sets were pretested to elicit feelings of safety/calmness and threat, respectively. In addition, the individual sound clips were congruent with a state of safety (low arousal, positive valence) or threat (high arousal, negative valence). Self-reports of perceived safety/threat and affect were not obtained in the current investigation in order to reduce demand effects and not give clues as to the true purpose of the study. However, as my primary hypotheses fall within the framework of the polyvagal theory—that the autonomic nervous system (ANS) is responsive to perceived safety or threat—I tested for changes in sympathetic/SNS activity (i.e., finger pulse amplitude) and parasympathetic/PSNS activity (i.e., RSA) from resting period to Safety and from resting period to Threat. Relative to the resting period, *t*-tests (conducted on log-transformed variables) revealed that RSA ($t(74) = -3.964$, $p < .001$) and finger pulse amplitude ($t(74) = -6.445$, $p < .001$) were significantly reduced during the Threat condition, a pattern that suggests participants were undergoing vagal withdrawal and greater sympathetic activation.[4] However, the same pattern of significant ANS changes emerged during the Safety condition as well, which was unexpected. All physiological measurements for the Safety and Threat conditions are shown in Table 2. Overall, the Threat condition appears to have successfully induced a physiological state of threat, whereas the Safety condition did not appear to induce a physiological state of safety.

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[4]The difference between proximal-assessment RSA and Safety RSA were not significantly different ($t(72) = -1.687$, $p = .096$). Proximal-assessment RSA and Threat RSA were also not significantly different ($t(74) = -1.059$, $p = .293$).

Despite the inclusion of a one-minute neutral slideshow between the Safety and Threat conditions, I tested whether or not there were significant order effects on ANS activity (i.e., RSA and finger pulse amplitude). To test the effect of order on RSA, a mixed-design ANOVA was conducted with condition as the within-participants factor (Safety vs. Threat) and the order as a between-participants factor (Safety sounds first vs. Threat sounds first). No significant main effect of order, condition, or the interaction between order and condition emerged for RSA. Model tests for finger pulse amplitude again showed no main effect or interaction effect of order. However, there was a significant main effect of experimental condition in the predicted direction, such that finger pulse amplitude was lower (indicating greater vasoconstriction and SNS activity) during the threat condition compared to the safety condition, $F(1, 72) = 4.748$, $p = .033$. Overall, even though the ANS measures during Safety and Threat were both different from the resting period (Table 2), a pattern of relatively greater sympathetic activity—indexed as lower finger pulse amplitude—was observed in the Threat condition.

Primary Analyses

Hypothesis 1: Under no external perceptions of safety or threat, higher resting RSA predicts greater levels of automatic facial mimicry. A multivariate general linear model was used to test whether and to what extent resting RSA predicted the degree of facial mimicry during the Control condition. Facial mimicry was operationalized as EMG activity in emotion-concordant muscle sites: OO and ZM activity during happy faces and CS activity during sad faces. These three sites served as the dependent variables, and the primary predictor was resting RSA (log-transformed); gender, BMI, and physical activity were also included as additional between-participant covariates, as these factors are known to influence RSA (Andrew et al., 2013; Berntson, et al., 1997). Contrary to Hypothesis 1, multivariate tests showed no significant effect of RSA at any mimicry site (Wilks' $\lambda = 0.953$, $F(3, 66) = 1.089$, $p = .360$, $\eta^2 = .047$). Model results are shown in Table 3.

Hypothesis 2. Under perceived safety, resting RSA moderates the change in automatic facial mimicry. Although psychophysiological evidence suggested that the safety-induction was ineffective, a mixed-design ANCOVA was nonetheless used to test the hypothesis that under perceived safety, resting RSA influenced automatic facial mimicry. Two within-participant factors—mimicry (EMG activity in OO during happy faces, ZM during happy faces, and CS during sad faces) and condition (Control, Safety)—as well as the between-participant factors of RSA, gender, BMI, and physical activity were included, as described above. There was no main effect of condition, $F(1, 66) = 1.552$, $p = .217$. Contrary to what was predicted, perceived safety did not change levels of mimicry. Furthermore, the critical interaction of RSA and condition did not emerge, $F(1, 66) = 1.142$, $p = .289$. Including the order of sounds presented as a factor did not alter the pattern of results with regard to overall mimicry within condition or effects of RSA. However, a significant interaction between order and mimicry type emerged, $F(1.852, 120.387) = 6.417$, $p = .003$; RSA had no significant effect on this difference. Bonferroni-adjusted pairwise comparisons showed that if Threat sounds had been played first, there was greater mimicry of sad faces during the Safety condition ($p = .010$). Order did not influence mimicry for happy faces.

Hypothesis 3. Under perceived threat, resting RSA moderates changes in automatic facial mimicry. To test whether RSA moderated facial mimicry under threat, a mixed-design ANCOVA was conducted; the within-participants factor (mimicry type) and between-participant covariates (RSA, gender, BMI, physical activity) were identical to those of

Hypothesis 2. The effect of order was tested as a between-participants factor, but it did not change the pattern of results, so here I present the more parsimonious model that omits order as a factor. Results are summarized in Table 4. A main within-participant effect of condition emerged, such that overall, people mimicked more when under perceived threat, compared to control ($M = 0.041$, $SD = 0.426$ for Control; $M = 0.231$, $SD = 0.429$ for Threat), which supports Hypothesis 3B, not 3A. There were no significant main effects of mimicry type, which is consistent with Hypothesis 1. Critically, as predicted, RSA significantly moderated the degree of facial mimicry under threat. Figure 3 illustrates this interaction. For participants with low levels of RSA, there was no significant change in mimicry between conditions, but participants with average-to-high RSA showed relatively greater mimicry under threat compared to control. Condition also significantly interacted with gender and BMI, which was unexpected. Males mimicked more than females in the control condition, but there were no gender differences in the Threat condition. People with low-to-average BMI showed a significant change in mimicry under threat, whereas people with higher BMI did not significantly change. There were no significant between-participant main effects of RSA or any covariates. Thus, the main effect of condition, as well as the interaction between condition and resting RSA support the predictions of Hypothesis 3B, but not Hypothesis 3A.

Discussion

The aim of this study was to test core tenets of the polyvagal theory—that the vagus nerve exerts influence on social engagement behaviors, and that its influence depends on perceptions of safety or threat. Specifically, I tested whether and to what extent tonic levels of RSA moderated automatic facial mimicry in neutral, safe, and threatening contexts. The face viewing task I used, which was composed of happy and sad faces, elicited differentiable patterns of EMG activity indicative of automatic facial mimicry: greater orbicularis (OO) and zygomaticus (ZM) activity during happy faces, and greater corrugator (CS) activity during sad faces. Overall, I found partial support for my hypotheses. Analyses did not support Hypothesis 1, that resting RSA (an index of cardiac vagal tone, CVT) was related to facial mimicry under neutral conditions. I found no support for Hypothesis 2, that RSA moderated changes in mimicry following a safety induction; however, physiological measures revealed that participants overall experienced vagal *withdrawal*, not vagal elevation. Crucially, I did find evidence for Hypothesis 3B: Relative to facial mimicry under neutral conditions, resting RSA positively moderated the degree to which people mimicked under threat. There was a main effect of condition, such that overall individuals mimicked more under threat than under neutral conditions. This finding diverges from the polyvagal theory, which implies that threat would reduce affiliative behavior (Porges, 2011), but is congruent with a wide body of literature that has found increased affiliation under threat (for a review, see Taylor & Lobel, 1989). Thus, participants with low RSA tended to mimic the same amount, before or after a threat induction; participants with mean-to-high levels of RSA mimicked more after a threat induction, compared to no threat induction.

Although the psychological mechanisms are unclear, I speculate that the relationship between resting RSA and greater facial mimicry during threat may be related to social affiliation motives. Several studies have shown that behavioral mimicry is modulated by the mimicker's goals. For instance, participants with a goal to decode emotional expressions mimic more than when there is no goal (see Hess, Hühnel, van der Schalk, & Fischer, 2016), and participants mimic more in cooperative vs. competitive contexts (Lanzetta & Englis, 1989). In a study of behavioral mimicry, Lakin, Chartrand, and Arkin (2008) found that people who had recently been socially excluded tended to mimic a confederate more than the participants who had been included. Altogether, these studies suggest that motivation has an impact on nonconscious mimicry. I speculate that a physiological state of threat may provide the motivation to seek social support, for those with higher levels of RSA. Indeed, indices of higher cardiac vagal tone have been positively associated with social approach behavior under stress (Geisler et al., 2013), prosocial behavior in novel contexts (Sahdra, Ciarrochi, & Parker, 2015), resilience and wellbeing (for a review, see Whitson & El-Sheikh, 2003). Together with findings from the mimicry and cardiac vagal tone literature, my results suggest a possible behavioral mechanism through which higher parasympathetic control builds resilience and social resources. Enhanced automatic facial mimicry during threat may enable individuals to better understand the emotions of others—one precondition for building relationships. Secondly, because greater mimicry is associated with higher likability, people with greater resting RSA may be better positioned to form positive social connections with others. Instead of "retreating" during a threat and engaging less with those around them, for some people, resting RSA may explain how threats or challenges are transformed into social opportunities that help build resources. Consequently, this greater propensity to affiliate with others may engender opportunities to experience positive emotions, which in turn may potentially counteract emotional "downward spirals" that can lead to the development of mood disorders (Garland et al., 2010). Relatedly, it has been found that for resilient individuals, positive emotions partly serve as a way to recover from negative experiences (Tugade & Fredrickson, 2004). Therefore, it is possible that facial mimicry is one behavior through which individuals can "tap into" potential social resources in times of need, which aids in building resilience and counteracting the potentially detrimental effects of stress.

My within-participants study design allowed meaningful comparisons of EMG activity across conditions. Due to substantial inter-individual variability in EMG activity, it is otherwise difficult to reveal differences in purely between-participants designs. Conversely, the within-participant design cannot fully account for the possibility that there were carryover effects from one condition to the next (e.g., affective carryover from threat to safety, or differences in face processing across successive face blocks). For instance, because the control condition necessarily preceded the threat and safety inductions (to prevent potential affective carryover effects), it is possible that individuals simply mimicked more in later blocks than early blocks. I speculate, though, that this is not the case, as there were no significant changes from Control to Safety. Indeed, my failure to support Hypothesis 2 strengthens the claim that the findings of Hypothesis 3 are due to a Threat induction, not just an order effect. Alternatively, it could be argued that it is simply arousal (and not specifically threat) that leads to enhanced mimicry. However, because I found that physiological arousal was higher in both the Threat *and* Safety conditions relative to the resting period (an unexpected result), the relationship between threat and mimicry cannot be fully explained by physiological arousal alone.

There are several other limitations of this study beyond the constraints of the within-participants design. Primarily, the relationship between resting RSA and facial mimicry is correlational, so causal interpretations are not warranted. For example, one could make the case that people who tend to engage in threat-enhanced behavioral mimicry are able to build richer social networks and resources. In fact, it has been shown that cardiac vagal functioning and social connectedness may reciprocally influence one another (Kok & Fredrickson, 2010), so it is possible that the ability to more easily form social connections (e.g., through greater facial mimicry) aids in the development of higher parasympathetic control of the heart.

Furthermore, the null finding in the Safety condition may be due to the fact that the safety induction likely failed. Even though the auditory stimuli set had been pre-tested to produce subjective experiences of calmness and safety, participants' physiological state did not reflect a biopsychological state of safety. True perceived safety, as defined by the polyvagal theory, requires increased activation of the parasympathetic nervous system and downregulation of the sympathetic nervous system (Porges, 2011). During the safety induction, there was overall a decrease in RSA and a decrease in finger pulse amplitude (i.e., greater sympathetic activity), relative to the resting period. Without self-reports of affect or emotion directly following each condition, I cannot make unequivocal assumptions about the experiential state of the participants. Considering MTurk ratings of the auditory stimuli sets gathered as pilot data, along with the observed patterns of physiological change, it appears that the safety-induction may have functioned more as a mild positive emotion induction. I had originally selected the presentation of 20, 6-second audio clips to most closely mirror the threat induction. However, the content of individual sound stimuli encompassed a wide range of pleasant sounds, from rainfall to children laughing. Because of their brief and diverse nature, the clips played for the safety induction may have unintentionally increased vigilance and attention, which are cognitive states associated with vagal withdrawal (see Muhtadie et al., 2015), counteracting the potential for effectively inducing perceived safety.

In addition, there is no consensus on best practices for the analysis of facial EMG data, and the state of the science on this topic has not changed much since Fridlund and Cacioppo's published guidelines (1986). Empirical studies typically take one of three approaches. First, many studies transform EMG data to have a normal distribution that is robust to voltage differences due to electrode placement or facial morphology. Typically, this is achieved by either log-transforming or standardizing EMG signals (e.g., Hess & Blairy, 2001). In this study, the analyses I conducted were on data derived from this approach. Others account for within-participant EMG variation by utilizing a percentage score, usually derived by dividing experimental-trial EMG activity by pre-trial baseline activity (Niedenthal, Winkielman, Mondillon, & Vermeulen, 2009). Others simply use raw microvolts as their unit of analysis (e.g., Dimberg, Thunberg, & Elmehed, 2000). However, face morphology differences among participants and among muscle sites may produce systematic differences in microvolts. Thus, I opted to transform EMG activity into within-participant standardized difference scores, which is typical in the facial mimicry literature. Further research is needed to establish best practices for facial EMG analysis for various study designs.

Interpretative caveats of EMG data or RSA aside, I found support for the claim that under perceived threat, participants mimicked happy and sad faces to a greater extent than under neutral conditions, and that this effect depended on a tonic measure of cardiac vagal tone (resting RSA). Specifically, this enhanced mimicry under threat was not present for participants with low RSA, yet greater for people with higher levels of RSA. However, the influence of resting RSA appeared to be specific to the context of perceived threat; resting RSA did not appear to be associated with automatic facial mimicry under neutral conditions or under a state of perceived safety.

CHAPTER 3: STUDY 2

Study 1 sought to explore how, under conditions of perceived threat or perceived safety, people's underlying biological traits (i.e., tonic levels of parasympathetic vagal activity, measured as baseline RSA) may predict the degree to which they engage in automatic affiliative behavior, specifically facial mimicry. Expanding from this work, in Study 2 I attempted to more finely understand the dynamic role that vagal activity may play in automatic affiliative behavior. Thus, instead of measuring *behavior* under perceived threat or perceived safety, I measured *vagal activity* across different contexts to explore how these measures impinge on prosocial behavior. In this way, I aimed to capture *vagal flexibility*—the ability to appropriately regulate parasympathetic activity in response to the demands of the situation—which has been shown recently to be a marker of social sensitivity (Muhtadie, Koslov, Akinola, & Mendes, 2015) and altruistic behavior (Miller, Kahle, & Hastings, 2015; Bornemann, Kok, Böckler, & Singer, 2016). Then, I tested whether this measure was related to a behavior that ostensibly involves both social sensitivity and caretaking behavior: expressing compassion. To this end, I pinpointed three channels through which expressed compassion may vary among individuals: 1) prosodic/acoustic elements of the voice, including pitch and loudness, 2) subjective, listener-perceived compassion of content-filtered (i.e., words removed) messages, and 3) linguistic elements that are largely independent of vocal prosody but may nonetheless be important factors in conveying compassion/emotional support.

Assessing Vagal Flexibility

The existing concept of *vagal flexibility*, according to Muhtadie and colleagues (2015), is broadly defined as "dynamic modulation of cardiac vagal control" (p. 106), and was operationalized as the difference between RSA at rest and RSA activity during attentional demand. Their specific measure of vagal flexibility was reverse-scored such that higher scores indicated a decrease from baseline to the attention task (i.e., vagal withdrawal). In their regression equations, they included the main effects of baseline RSA and the vagal flexibility score. For the current study, I was interested in expanding this concept of vagal flexibility to include measures of cardiac vagal activity at baseline, during attentional demand, *and* within a safe context. Thus, similar to Muhtadie and colleagues (2015), I measured RSA at rest and during attentional demand (i.e., to assess vagal withdrawal). In addition, I measured RSA during meditation (a safe context) to assess vagal elevation, and computed the difference score such that higher vagal elevation indicated an increase in RSA from baseline to meditation. To determine the unique and combined effects of these two different measures of RSA reactivity, I tested three models, all of which included baseline RSA. The first model included a vagal withdrawal term; the second model included a vagal elevation term, and not vagal withdrawal; and the third included a combined measure (sum score) of vagal withdrawal and vagal elevation.

Assessing Expressed Compassion

The goal of this study was to explore whether and how measures of vagal flexibility predicted the effective expression of compassion. To do this, I targeted both the paralinguistic and linguistic elements of spoken messages. Paralinguistic components, which include the prosody or melody of speech, can be analyzed at an objective (i.e., acoustic parameters) and a subjective (i.e., listener perception) level. Acoustic parameters only reflect soundwave properties and are purely objective. Conversely, content-filtered speech perceived by listeners is subjective and largely non-overlapping with acoustic analyses, since listeners only heard filtered and distorted messages so that no words could be deciphered. Finally, linguistic features capture unique elements of spoken messages that cannot be ascertained through soundwave properties or listener-perceptions of content-filtered messages.

Acoustic cues. Although the vocal prosody of compassion has not been previously studied, I speculated that it has affective and socially functional features that overlap with expressions of love/tenderness and sadness, since compassion has been described in the literature as a blend of sadness and love (for a review, see Goetz, Keltner, & Simon-Thomas, 2010). Indeed, one study that examined another medium of nonverbal behavior—facial expression—found that greater felt sympathy was associated with greater facial displays of sadness, especially for those who had undergone compassion training (Rosenberg et al., 2015). Thus, there is some evidence that compassion and sadness have meaningful overlap in their nonverbal cues. In the nonverbal vocal expression literature, sadness and love show similar acoustic profiles to one another: lower pitch, less pitch variability/range, lower intensity, and lower intensity variability/range (Juslin & Laukka, 2003). Thus, like love and sadness, compassionate messages may have relatively reduced pitch and relatively reduced intensity.

Listener perceptions. Normal speech is perceived as a combination of linguistic and paralinguistic factors, which have bidirectional effects on the meaning and effectiveness of messages (Ishii, Reyes, & Kitayama, 2003). Here, I have cleaved these two elements apart and consider perceptions of "content-filtered" messages (i.e., words undiscernible). Without words present, people are nevertheless fairly accurate at identifying emotion within content-filtered messages (Scherer, 2003). Likewise, one study found that independent ratings of ten-second clips of content-filtered physician-patient interactions were significantly associated with patient satisfaction (Haskard, Williams, DiMatteo, Heritage, & Rosenthal, 2008). Thus, ratings of content-filtered messages can provide a useful method by which to assess the perceived compassion of the speaker.

Linguistic content. Compassionate messages may also contain linguistic clues as to how people convey compassion and emotional support. Because vagal activity has been linked to a) socially-oriented behaviors (e.g., Geisler et al., 2013), b) positive emotions in social contexts (Oveis et al., 2009; Isgett et al., 2017), and c) stress vulnerability (Thayer, Ahs, Fredrikson, Sollers, & Wager, 2012), vagal activity may also be related to the amount of socially-focused language, positive emotion words, and stress-related words in messages of compassion.

Research Aims

The first aim of this study was to establish the validity of my expanded definition of vagal flexibility by measuring vagal activity across three contexts: during a resting baseline (to index cardiac vagal tone), during a challenging task (to elicit vagal withdrawal, or decreases in RSA), and within a safe context (to elicit vagal elevation, or increases in RSA). My second aim was to take a multi-method approach to assess the degree to which people effectively express compassion. Finally, these two facets (vagal flexibility, expressed compassion) formed the foundation of this study's empirical approach to test my hypothesis. Specifically, I hypothesized that *greater vagal flexibility (indexed by vagal withdrawal, vagal elevation, or a combination of both) predicts the extent to which spoken messages convey cues of compassion and emotional support, through a) enhanced prosodic cues (relatively lower measures of pitch* *and intensity), b) greater listener-perceived compassion,, and c) differentiable linguistic content (more socially-focused language, more positive emotion words, and fewer anxiety-related words).* Subsequent exploratory hypotheses will examine potential quadratic relationships of baseline RSA with prosocial outcomes (Kogan et al., 2014), and whether vagal flexibility predicts a dichotomous behavioral measure of enacted compassion (i.e., whether participants obtain copy of their message to share).

Method

Participants

107 undergraduate students (70% female; M_{age} = 18.67, SD = 0.86) in an introductory psychology course at the University of North Carolina at Chapel Hill completed the study for course credit in the Fall semester of 2016. Per information provided in the recruitment ad, participants needed to be at least 18 years old and not engaged in regular meditation practice. Eighty percent of participants self-identified as Caucasian, 16% as Asian or Pacific Islander, 8% as African-American, and 3% as American Indian. Participants were allowed to select more than one race, and 7% identified as two or more races. Seven participants self-identified as Hispanic or Latino.

Measures

Cardiovascular activity. An electrocardiogram (ECG) and impedance cardiograph were obtained to measure heart rate and impute respiration. Disposable snap electrodes were placed in bipolar configuration. One electrode was placed on the participant's right clavicle, and one was placed on the left side of the lower ribs; a ground electrode was placed on the opposite side, at the right lower ribs. To measure cardiac impedance, electrodes were placed on the ventral and dorsal sides of the torso. Ventral electrodes were placed at the top and bottom of the sternum near the solar plexus; dorsal electrodes were placed on the spine, each about 3 cm higher and lower than the two ventral electrodes, respectively. The distances between the two ventral electrodes and between the two dorsal electrodes were measured in centimeters.

Respiratory sinus arrhythmia (RSA). Raw recordings of heart rate and impedance were acquired continuously at a sampling rate of 1000 Hz using an integrated system and software package (BioLab 3.2.1, Bionex chassis; Mindware, Westerville, OH, USA). Heart rate data were preprocessed and manually edited to correct for artifacts using Mindware software (HRV 3.1.2; Mindware, Westerville, OH, USA). If an R-spike was missing (based on an inter-beat interval algorithm), a midbeat was estimated and inserted between the two adjacent R-spikes; out of over 50 hours of recorded physiology for the full sample (N = 107), there were a total of 31 instances where an R-spike was inserted, across ten participants. If midbeat edits or high levels of noise represented more than 10% of the R-spike in a given 1-minute bin, the bin was not used in analyses (only one bin in one participant was excluded for this reason). Edited data were submitted to the Fast Fourier Transformation, and RSA was determined by taking the natural log of the high-frequency power band of heart rate variability. In the primary analyses, RSA was calculated as the mean of all 1-minute bins within each task: for the baseline, attention task, and guided meditation.

Electronic questionnaires. Participants were administered a battery of questionnaires, descriptions of which can be found in Appendix A. After ECG electrode placement but before physiological recordings began, participants completed the meditation screening questions, naming task, a personality assessment, and physical activity questionnaire. After they completed the tasks and webcam recordings, towards the end of the session, they were assessed on (in the following order): inclusion of other in self (IOS) for certain relationships, giving emotional support in certain relationships, empathic accuracy (RMET), group entitativity, social approach/avoidance motives, prioritizing positivity, and demographics.

Meditation screening. Although participants were only eligible of they were not experienced with meditation, I administered two questions at the beginning of the study that assessed how much experience participants had with meditation, and how frequently they currently meditated (if at all).

Naming task. At the beginning of the study, participants provided the names of several people who fit various descriptions. Although the task was primarily used to distract participants from the primary relationship of interest (i.e., between participants and the person they identified as suffering), a variety of relationships were assessed. Participants were instructed to "*think about your various social connections (people you know, not celebrities or fictional characters)"* and provide the name of a person in their lives who best fit each of six descriptions. For the six names provided, they were asked not to select a name more than once, and were ensured that the names or initials they had provided would be confidential.

For my primary relationship of interest, I asked participants to name "*Someone who is suffering in some way, big or small. For example, someone who is struggling with mental or physical illness, grieving the loss of a loved one, or having a specific problem in their day-to-day life."* They were also asked to name someone whom they appreciated, admired, envied, tried to avoid, and considered an acquaintance. For all relationships, they were asked to classify the relationship (e.g., friend, romantic partner, family member, co-worker/classmate, roommate, or other).

Recorded webcam messages. Participants were instructed to make two webcam recordings addressed to the person in their lives who was suffering. One recording (Control) involved giving directions, and the second (Expressed Compassion) involved expressing support or compassion (see Procedure below). Webcam recordings were analyzed using three approaches: 1) acoustic analysis, in which quantitative properties of recordings were extracted, 2) content-filtered analysis, in which online, untrained listeners provided subjective ratings, and, 3) linguistic analysis, in which spoken words were first transcribed and then analyzed. Details are described under "Data reduction of audio messages."

Body mass index (BMI). Participants' height and weight were instrument-recorded at the end of the lab session to calculate BMI.

Procedure

Each participant arrived at the lab for the study entitled "Social Connections and Psychophysiology." The examiner asked all participants to remove any metal jewelry, bulky sweaters, or wearable electronic devices that could interfere with sensor readings. After being given an overview of the study—including explaining that they would be video-recorded during the session—and obtaining informed consent, the examiner then placed ECG and impedance electrodes on the participant and attached the leads to a chassis. Participants were then seated in a comfortable chair at a desk that contained a laptop and desktop monitor; the video camera was in plain sight, so the examiner ensured that audiovisual data collected were confidential. After checking that the ECG signal was clear on the acquisition computer, the examiner instructed the participant to begin completing a set of questionnaires on the laptop when she left the room. At that point, the examiner left the room and closed the door. Participants completed several self-report measures, including the naming task (see "Measures" above). After they reached a stopping point in the survey, the experimenter instructed them through an intercom to turn towards the desktop computer to begin the next part of the study.

Resting baseline. A five-minute, free respiration baseline was recorded. Thus, after participants finished the first set of questionnaires, the experimenter informed them that they next were to provide a baseline reading, and that they should "not think about anything in particular, just relax," and also that they should try to maintain straight posture and not lean back against the chair for the duration of the study (recommended protocol, as described in Laborde, Thayer, & Mosley, 2017). Instructions were also on the computer screen to remind participants to wait for several minutes until the baseline was over.

Neutral slideshows. Before each task, participants were instructed to watch a 45-second slideshow that contained neutral images from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2008). In total, there were 20 images that were presented for 2.25 seconds each.

Attention task. Using E-Prime 2.0 software (Psychology Software Tools, Sharpsburg, PA, USA), a visual attention task was used to obtain a measure of vagal withdrawal. During focused attention, parasympathetic activity should withdraw, and this change can be used as an index of vagal flexibility in response to a challenge (Muhtadie et al., 2015). Previous studies have used a visual dot-tracking task (Cavanagh and Alvarez, 2005) to elicit vagal withdrawal (Muhtadie et al., 2015). However, due to incompatibilities in lab software, I chose a different task that was also visual in nature. This was the short-form Symmetry Span (Foster et al., 2015), which has been used in the field of cognitive psychology as an exercise that predicts working memory capacity. Although the two tasks are different from a cognitive psychological perspective—one aims to measure multifocal visual attention, while the other seeks to measure working memory capacity—they bear similarities for the purpose of creating a context of challenge and are fairly robust to differences in reading ability. Moreover, both tasks are visual in nature and have no social content. In the task used here, participants were instructed to remember the sequence of red boxes that flashed on the screen, while intermittently making judgments about pictures. First, participants were given brief instructions and practice items before the task blocks began. The task consisted of a sequence of three to five trials per block. For instance, in one trial, a participant would see one square flash red in a 3-by-3 matrix. Then, he or she would see a geometric picture and indicate whether or not the picture was symmetrical. Another square would flash red; another geometrical picture judgement would be presented; and a third square would flash red. Finally, the participant would need to remember and select the particular sequence of red squares that flashed during the trial. Participants were instructed to do the task as quickly and as accurately as possible. Because it was self-paced, the entire task ranged from 3 minutes to 8 minutes, with most participants taking about 5 minutes to complete.

Guided meditation. All participants completed a guided meditation that lasted just under 20 minutes. Before the meditation began, participants were instructed to sit up straight and keep their eyes open during the meditation, gazing gently at a smooth river stone that had been placed near the computer. Participants were also reminded to pay attention and to try not to fall asleep. An open-eyed meditation was chosen to reduce the risk that participants would fall asleep. The guided body scan meditation used in this study has been shown in a previous study to induce vagal elevation (Ditto, Eclache, & Goldman, 2006). The audio was from the first 20 minutes of the first track in a series of guided meditations produced by Jon Kabat-Zinn, used in the Mindfulness-Based Stress Reduction Clinic at the Center for Mindfulness, University of Massachusetts (mindfulnesscds.com). The audio file was edited to end at a logical stopping point.

Webcam recordings. After the baseline and tasks had ended, participants continued with the survey. After answering several questions about the tasks (i.e., difficulty and effort of the attention task, whether or not they fell asleep during meditation), they were instructed to make two webcam recordings. For both recordings, they were asked to record a message to the person they had listed as suffering; piped text was used to provide the name from earlier in the survey. The first recording was the Control message, and the second was the Expressed Compassion message. This order was maintained for all participants to reduce potential affective carryover effects from the Expressed Compassion recording to the Control.

Control message. First, all participants put on a headset with a microphone, and were instructed to look into a webcam. Participants were then asked to record a message to the person, describing how to get from a popular landmark on the university's campus to a nearby street. The instructions mentioned the suffering person's name with no references to suffering (i.e., "Imagine you are talking to the person you named *John…*"). Next, all participants were instructed "to be as detailed as possible, so that this person would be able follow directions, even if they had never been to UNC." They had up to two minutes to make the recording. Only one participant did not know where the street was, so she was asked to give directions to a different building. After participants finished, they proceeded to read instructions for the second recording.

Expressed compassion message. For the second prompt, participants read instructions that were modified from an expressed gratitude task (Algoe, Fredrickson, & Gable 2013), but with expressed compassion as the target of interest: "We are interested in how people provide support for their friends and family. We'd like you to think of *John*, whom you indicated was suffering in some way, big or small, and for whom you feel compassion. We ask you to record a message to this person, expressing your support." After reading this prompt, participants had up to two minutes to record a message to that person.

Enacted compassion and study conclusion. After participants finished the recordings, they completed the rest of the questionnaires. Once they were finished, the experimenter re-entered the room, removed the sensors, and took measurements of height and weight using a scale. After that, the experimenter read a script to debrief the participant, explaining that they had been asked to record a message to someone who was suffering. Then, the experimenter asked, "If you would like a copy of the recording to send to this person, we are happy to share the video with you. Would you like us to send you a copy?" After answering yes or no, the participant initialed an audiovisual release form, indicating whether they provided consent for their webcam audio to be used in research. Finally, the participant was thanked and dismissed.

Data Reduction of Audio Messages

***Acoustic analysis*.** The audio content of the first 30 seconds of each recording was used as the basis for analyzing two types of acoustic cues: fundamental frequency (i.e., pitch, measured in Hz) and intensity (i.e., loudness, measured in dB). Several measures of central tendency and dispersion were calculated for both pitch and intensity, including mean, variability (i.e., standard deviation of audio sample), and range. For most speech pathology and linguistic research purposes, the unit of analysis is the syllable or phoneme. However, due to the naturalistic speech task, no two messages contained the same linguistic content. In addition, my research question concerned *global* acoustic features (i.e., prosody) at the level of a spoken message, not at the level of individual words. Accordingly, the first 30 seconds of speech were selected to capture global acoustic features with comparable acoustic input across participants; if participants provided samples shorter than 30 seconds, the entire message was used.[5] Using the freely available phonetic analysis software Praat (version 6.0.19), 20-ms bins were used as the unit of analysis within each 30-second message (a timeframe suggested by Juslin & Scherer, 2008). Within each bin, pitch and intensity information was extracted. For pitch, the standard filter range of 75 to 500 Hz was applied, which is the feasible pitch range for adult human speech (males and females). Mean, minimum, and maximum pitch were calculated for each 20-ms bin. Unvoiced or silent portions of messages did not return any pitch values. For intensity, default program settings were applied to calculate the mean, minimum, and maximum intensity of each 20-ms segment. However, this returned values for unvoiced or silent segments of the messages, so only intensity values during voiced segments (i.e., pitch value present) were used in analyses. Thus, each message contained up to 1,500 data points (30 seconds of 20-ms bins), which were used to determine within-message mean and variability (i.e., standard deviation), for pitch and intensity. Minimum and maximum values were also extracted from each recording to calculate range for pitch and intensity.

Content-filtered analysis. To obtain listener ratings of the audio recordings, all messages were first content-filtered so that no words could be deciphered, while conserving paralinguistic elements (speech rhythm, emotional tone). The same 30-second (or less) audio clips used for acoustic analysis were used here. Using Audacity software (version 2.1.2), for each recording, a low-pass filter with 48 dB roll-off was applied and amplified so that peak amplitude = 0 dB. Depending on the participant's voice pitch and loudness, low-pass filters

[5]For the Control message, six participants provided samples of less than 30 seconds (from full sample, N = 107). For the Expressed Compassion message, 25 participants provided samples less than 30 seconds.

ranged from 300 – 400 Hz. Next, a research assistant listened to the content-filtered files, and, if words could still be deciphered, recordings were re-filtered at a lower frequency.

Next, a sample of 226 online Amazon Mechanical Turk participants (“listeners”) were used to rate the content-filtered audio clips from lab study participants (“speakers”) on several dimensions. Each listener received six audio clips to rate (in randomized order): three from the Expressed Compassion condition and three from Control condition. After listening to each clip, they were asked, “*Based solely on the vocal sample you just heard, how would you rate this person?”* on nine dimensions: compassionate, caring, supportive, pleasant mood, unpleasant mood, warm, competent, and dominant. Listeners were also asked to identify the speaker’s gender and indicate whether or not they could decipher words. Finally, listeners completed brief demographic information (age, gender, race/ethnicity, level of education, employment, and English-speaking status).

Five total attention checks were used to ensure quality of the data. The first one (before any audio clips) asked participants which planet they were on. Additional attention checks were presented for three of the message ratings (e.g., “Please select ‘2’ for this item”). A final attention check in the demographic questionnaire required the absence of a response. MTurk participants were eliminated if they failed one or more checks (n = 19) or were non-English speakers (n = 1). Thus, a final sample of 206 listeners provided ratings, with each clip being rated by a unique listener on average 6.06 times.[6] Mean ratings of each dimension for each audio clip were calculated across listeners of that clip.[7]

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[6]Due to imperfect survey randomization and MTurk participants who failed attention checks, not every message was rated exactly six times, but all received a minimum of five ratings and a maximum of eight.

[7]Two participants from the lab study did not consent to have their webcam recordings used for research, so their recordings were not part of the pool of recordings MTurkers rated.

Linguistic analysis. Messages from the Expressed Compassion task were transcribed by trained assistants and double-checked for accuracy. In accordance with guidelines provided by the Linguistic Inquiry & Word Count (LIWC) 2015 User Manual (Pennebaker, Boyd, Jordan, & Blackburn, 2015), nonverbal utterances (e.g., chuckles, coughs) were not transcribed, and certain words and phrases were coded as fillers (e.g., "like," "you know"). All Expressed Compassion transcripts were analyzed with LIWC 2015 software (Pennebaker et al., 2015), which gives a range of descriptive information on individual text files; for instance, it provides percentages of words used from various dictionaries, or groups of words that fall under a certain category (e.g., positive emotion words). For this study's analyses, I examined the percent of words classified as social and affiliative, positive emotions, and anxiety-related.

Results

Preliminary Analyses

Before running analyses, several participants were excluded a priori. First, two participants were excluded because they did not fit eligibility criteria: those who self-reported being experienced (three weeks or more) or frequent (once a month or more) meditators. Four participants were excluded because they were not fluent in English. I also inspected all video-recordings during meditation and judged whether or not participants had fallen asleep (presence of "dozing" behavior, like head drooping and jerking awake). Although only 4 participants reported having fallen asleep, I found that a substantial number (16 of remaining sample) fell asleep during the guided meditation. These people were excluded from all analyses. However, the inclusion of these individuals in primary analyses did not change the pattern of results (unless otherwise noted). Thus, after removing the six ineligible participants and those who fell asleep, a final analysis sample of $N = 85$ remained.[8]

Manipulation check: Visual attention task. Participants were asked on a 5-point scale to report the difficulty of the visual attention task (1 = "Not at all difficult" to 5 = "Very difficult") and how much effort they gave (1 = "Hardly any effort" to 5 = "All my effort"). On average, participants reported that they found the visual attention task moderately difficult ($M = 2.51$; $SD = 0.76$), and engaged in a moderate-to-high amount of effort ($M = 3.82$; $SD = 0.93$). Task difficulty and effort were not significantly correlated ($r = .15$, $p = .17$), and the order of the attention task and guided meditation did not affect perceived task difficulty or effort.

Manipulation check: Message recipient's suffering and self-reported compassion. After recording the webcam messages, participants were asked to rate on a 7-point scale the seriousness of the message recipient's suffering and how compassionate they felt toward the recipient (1 = "Not at all" to 7 = "Extremely"). No participants reported that the recipient's suffering was not at all serious, and no participants reported that they did not at all feel compassion. On average, participants rated the recipient's suffering as moderate ($M = 4.78$, $SD = 1.26$) and reported feeling high levels of compassion ($M = 5.98$, $SD = 1.15$). These ratings between perceived seriousness and compassion were correlated ($r = .47$, $p < .001$). Nearly half (48%) of participants listed a friend as the person who was suffering; 39% listed a family member; 4% listed a coworker or classmate; 5% listed a roommate; and nearly 5% listed a different type of relationship.

[8]Due to frequent software malfunctions, six participants of the final sample had incomplete physiology data (3 had no physiology recorded; 2 were missing only the baseline recording; 1 was missing attention task and meditation recordings), and three additional participants were missing audio data. Thus, analyses that rely on all three physiological measures *and* both audio messages have $N = 76$.

Establishing the validity of vagal flexibility. My first research aim for this study was to establish the validity of my measure vagal flexibility. In order to be able to compare the unique and combined effects of vagal activity within different contexts, it was necessary to ensure that the tasks designed to measure vagal withdrawal and vagal elevation, respectively, actually elicited the predicted pattern of vagal activity for most participants.

Vagal withdrawal (VW). Baseline RSA (average across five minutes) and RSA during the attention task (average over the course of the task) were compared. As expected, the overall change in average RSA from baseline to the visual attention task was negative (M = -0.20; SD = 0.76), and significantly different from baseline within participants, $t(78) = -2.37$, $p = .020$. This suggests that the visual attention task effectively induced vagal withdrawal, although it is important to note that there was a range of responses (-2.63 – 1.61), with some participants exhibiting an opposite pattern from the group mean. Because I wanted to show the relationship between *greater* flexibility and expressed compassion, I multiplied participants' change scores by -1. This reverse-scored measure of vagal withdrawal (VW), was positively associated with baseline RSA ($r = .46$, $p < .001$), indicating that higher levels of baseline RSA predicted a greater capacity for vagal withdrawal. I considered the possibility that task difficulty and task effort may affect results, as an individual's effort and perceived difficulty might influence their RSA reactivity (although these measures were not correlated with RSA during the task). Thus, I ran all analyses separately with this covariate ("task challenge"), calculated as the mean of the task effort and task difficulty measures, with higher scores representing greater self-reported challenge. There was no effect of task challenge on any of the outcome variables and the pattern of results was identical, so for consistency, I report the more parsimonious models that do not include this covariate.

Vagal elevation (VE). Baseline RSA and RSA during meditation (average over the course of entire meditation) were compared. Again as expected, participants' average RSA significantly increased during the guided meditation (M = 0.21; SD = 0.60), and was significantly different from baseline RSA within participants (t(78), = 3.20, p = .002). There was also a range of responses (-1.21 – 1.74), but the majority of participants displayed a pattern suggestive of vagal elevation. Thus, the guided meditation was an effective method to increase RSA activity. Baseline RSA and VE were negatively correlated (r = -.49, p < .001), such that higher baseline RSA actually predicted *smaller* increases in RSA during meditation, indicating a possible ceiling effect. Furthermore, VW and VE difference measures were themselves significantly inversely correlated (r = -.46, p < .001), indicating that participants who were higher on one measure tended to be lower on the other measure.

Vagal flexibility (VF). A composite vagal flexibility variable was computed to account for an individual's ability to effectively regulate cardiac vagal activity in multiple contexts: during an attention task where metabolic demands may be greater, and during a meditation task intended to foster a safe context (i.e., meditation). Following the methodology developed to measure Expressive Flexibility (Bonanno, Papa, Lalande, Westphal, & Coifman, 2004; Westphal, Seivert, & Bonanno, 2010), which quantifies an individual's ability to enhance or suppress emotional expression, I similarly developed a measure of *vagal flexibility (VF-sum)*. VF-sum was taken as the sum of vagal withdrawal (reverse-scored) and vagal elevation change scores; higher VF-sum indicates an overall greater ability to regulate cardiac vagal activity in the "appropriate" direction (decreased RSA during attention task, increased RSA during meditation). About one-third of participants exhibited the appropriate pattern of change in both contexts, although most participants (57%) exhibited appropriate change for *either* VW or VE.

Six percent of participants showed the opposite pattern for both VW and VE. I expected that most participants would show some degree of sum vagal flexibility, and as predicted, participants on average exhibited positive vagal flexibility (*M* = 0.42, *SD* = 0.72).[9] The correlations among all RSA measures and covariates used in the primary analyses (sex, BMI, and physical activity) are shown in Table 5.

Statistical approach. As part of my first research aim, I sought to compare the predictive ability of vagal flexibility as previously conceptualized (which is only within a baseline-vs.-challenge framework) with my expanded conceptualization of vagal flexibility, which includes the baseline-vs.-challenge framework *and* a baseline-vs.-safety framework (vagal withdrawal and vagal elevation). One empirical question was whether vagal flexibility was a combination of the two types of responses, or if each type of response offered unique predictive ability that may be obfuscated by a composite measure. Thus, three sets of independent variables (IVs) were separately tested for each outcome variable, (10 outcomes * 3 IV sets = 30 models total). The first independent variable set (hereafter referred to as Set 1) tested the independent effect of vagal withdrawal (VW). The second independent variable set (referred to as Set 2) tested the unique effect of vagal elevation (VE). The third and final set (Set 3) tested if if vagal responses were most predictive as a sum score, vagal flexibility (VF-sum). Set 1, Set 2, and Set 3 all included the same *subset* of covariates. Specifically, all models regressed outcome variables on baseline RSA and three standard covariates known to influence RSA: biological sex (0 = female; 1 = male), BMI, and physical activity (Andrew et al., 2013; Berntson, et al., 1997). Age was not included due to low sample variability (participants were

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[9]One individual had a VF score that was > 3 SDs from the mean (VF = 3.87). However, this person was included in all analyses.

ages 18 to 21). Within a given outcome, if a significant effect was found for a measure of RSA, explanatory power (R^2) across Sets 1, 2, and 3 was compared.

Quantifying expressed compassion. My central research aim was to evaluate the relationship between vagal functioning and expressed compassion. To quantify Expressed Compassion, I used three distinct methods: A) extracting acoustic properties, B) obtaining listener perceptions, and C) analyzing linguistic content. From these three methods, I distilled the measurement of Expressed Compassion into a set of ten potential outcomes: from Method A, changes in pitch mean, pitch variability, pitch range, intensity mean, intensity variability, and intensity range; from Method B, listener-perceived compassion; from Method C, socially-focused language, positive emotion words, and anxiety-related words. Table 6 presents correlations that show how all outcomes interrelate. Whereas most of the variables showed independence from one another, some relationships do emerge. Within Method A, change in pitch variability and pitch range were correlated, which is expected since they are both measures of dispersion. Likewise, all intensity measures were moderately correlated with one another. Listener-perceived compassion (of content-filtered messages) was positively associated with the amount of socially-focused language used, which provides evidence of convergent validity for these two methods. Furthermore, socially-focused language was inversely associated with anxiety-related words, and significantly and positively related to participants' perceived severity of message recipient's suffering, as well as the participants' self-reported experienced compassion. Because pitch variability and pitch range were moderately correlated, these variables were tested using a multivariate approach. Similarly, intensity mean, variability, and range were also tested using a multivariate approach. Thus, the final set of variables comprise the following outcomes: changes in pitch mean, changes in pitch variability/range, changes in acoustic intensity measures, listener perceived compassion, socially-focused language, positive emotion words, and anxiety-related words.

Conceptual replication: Vagal flexibility and empathic accuracy. Before I tested my primary outcome measures of Expressed Compassion, I sought to establish the validity of vagal flexibility measures by conceptually replicating the finding by Muhtadie et al. (Study 3, 2015), that vagal flexibility significantly predicted empathic accuracy as indexed by the RMET. However, there were a few important differences. First of all, the attention tasks used to elicit vagal withdrawal were not identical, although they bear important similarities: the tasks were both highly visual in nature (dot-tracking vs. visual sequence and symmetrical images) and non-social. Critically, both tasks overall elicited vagal withdrawal at similar magnitudes (-0.13 in Muhtadie et al. Study 3; -0.20 reported here), and both tasks observed a range of responses, from decreased RSA to increased RSA. Second, performance on these tasks was necessarily assessed differently; Muhtadie et al. ostensibly used accuracy as a measure of task performance, whereas I used self-reported effort and difficulty. Third, in Muhtadie et al. (2015), verbal intelligence was assessed in a community-based sample and used as a covariate, which was a significant predictor of RMET score. I did not assess verbal intelligence, so intelligence effects in my sample cannot be determined. Finally, Muhtadie and colleagues included age, sex, and BMI as covariates that influence RSA. For purposes of replication, I included these three covariates. When I tested this model in my analyses, the model was not significant $F(8, 66) = 0.333$, $p = .950$. Models run with the standard covariates present in other analyses (sex, BMI, physical activity; not age) showed the same pattern of results.

Next, I tested the effect of vagal functioning on RMET using Set 1 (included baseline RSA, vagal withdrawal, and standard covariates), which was not significant, $F(5, 69) = 0.494$,

p = .779. Next I ran a model with Set 2 (included baseline RSA, vagal elevation, and standard covariates), and this model was also non-significant, $F(5, 69) = 0.324$, $p = .897$. Finally, I used Set 3 (included baseline RSA, vagal flexibility sum, and standard covariates), and this model was, again, not significant, $F(5, 69) = 0.545$, $p = .742$. Because none of the models were significant, I did not compare model R^2 values. Thus, contrary to previously published work, in my sample I did not find evidence that vagal activity was related to empathic accuracy as measured by the RMET.

Self-reported compassion. To test whether and to what extent vagal function was related to participants' explicit self-reports of compassion (vs. measures of Expressed Compassion), the predictors of Sets 1 – 3 were tested in separate in multiple linear regressions, predicting the outcome variable of self-reported compassion. For all of the models, there were no significant effects for any RSA measures.

Primary Analyses

Method A: Does vagal functioning predict acoustic properties of expressed compassion?

Pitch and intensity properties. The acoustic properties of Control and Expressed Compassion messages are described in Table 7. A series of *t*-tests were conducted to determine if Control and Expressed Compassion messages exhibited different patterns of pitch and intensity. These differences were quantified by computing change scores for each acoustic cue—subtracting the acoustic property during the Control message from the acoustic property during the Expressed Compassion message—such that positive scores indicate an increase in that property (e.g., speaking louder) during the Expressed Compassion message. The difference scores for pitch and intensity cues exhibited normal distributions, with the exception of intensity mean and intensity range; thus, difference scores for these measures were derived from log-transformed intensity mean and intensity range, respectively. As expected, participants spoke at a significantly lower pitch and with a more restricted pitch range during the Expressed Compassion message compared to the Control message, although there was no significant difference in pitch variability. Moreover, participants tended to speak with significantly less intensity (i.e., quieter), and with less intensity variability and range. As described earlier and shown in Table 6, changes in pitch variability and pitch range were correlated, although these were not correlated with pitch mean. As expected, all three measures of intensity were correlated with each other (Table 6).

The effect of vagal function on pitch cues. I tested whether and to what extent RSA activity (i.e., vagal flexibility) had an effect on changes in pitch cues while expressing compassion. Because it was not correlated with pitch variability or pitch range, pitch mean was tested separately (univariate GLM) from pitch variability/range (multivariate GLM). Again, Set 1 tested the independent effect of vagal withdrawal (VW); models with Set 2 tested the effect of vagal elevation (VE); models with Set 3 tested the effect of vagal flexibility (VF-sum). For all three pitch outcomes (mean, variability, and range), no overall models were significant (p-values ranging from .235 – .988), and neither multivariate tests nor univariate tests revealed significant effects of RSA measures.

The effect of vagal function on intensity cues. Next, I tested the effect of RSA on voice intensity cues (mean, variability, range) using a multivariate GLM, with the same predictors as described above for Set 1, Set 2, and Set 3. In Set 1, there was an overall significant effect of baseline RSA (Wilks's $\lambda = .877$, $F(3, 67) = 3.137$, $p = .031$, partial $\eta^2 = .123$). As shown in Table 8, baseline RSA was significantly associated with change in mean intensity, in the predicted direction: higher baseline RSA was associated with greater reductions in mean intensity when expressing compassion. No effects of baseline RSA were found for intensity variability or range. In models with Set 2, baseline RSA remained significant, although the univariate tests showed an effect of baseline RSA for intensity variability only, opposite of the predicted direction (see Table 8). There were no significant effects for any RSA measures using Set 3. As shown in Table 8, none of these models were overall significant (*p*-values ranging from .057 to .377), although three were marginally significant (Set 1 for intensity mean, Set 1 for intensity range, and Set 3 for intensity range).[10]

Method B: Does vagal functioning predict subjective perceptions of compassion?

Perceived compassion. Three of the dimensions described under "Content-filtered analysis"—how compassionate, caring, and supportive the participant seemed—served as my measure of perceived compassion in analyses. Although only three items, there was high reliability among the items for both Expressed Compassion messages (Cronbach's α = .96) and Control messages (Cronbach's α = .95). Thus, to obtain my dependent variable of listener-perceived compassion, I took the mean rating of three items (compassionate, caring, supportive) for each recording. Although only at the level of a trend, there were within-participant effects of perceived compassion, such that a given participant was rated similarly for his or her Control message and Expressed Compassion message (r = .21, p = .066). Furthermore, there was a significant effect of participant sex, such that females were rated significantly more compassionate than males, $t(77) = 2.63$, $p = .010$. On average, Expressed Compassion messages were rated as moderately compassionate (M = 3.83, SD = 0.62) and

[10] Including those who fell asleep, univariate tests using Set 2 (model $F(5, 84) = 2.372$, $p = .046$) and Set 3 (model $F(5, 84) = 2.629$, $p = .029$) found an effect of baseline RSA for intensity *mean* in the *predicted* direction ($B(SE)$ = -0.007(0.003) , p = .014 [Set 1], p = .009 [Set 3]).

scores exhibited a normal distribution. Surprisingly, Expressed Compassion messages were not rated significantly different on compassion than Control messages, $t(78) = -0.79$, $p = .431$, likely due to within-participant associations. Thus, ratings for Control messages were included as covariates in the following analyses.

The effect of vagal function on perceived compassion. I hypothesized that vagal functioning (i.e., baseline RSA and vagal reactivity) would be related to the degree to which content-filtered Expressed Compassion messages were perceived as compassionate. Different from the models in Method A, perceived compassion ratings of Control messages were included in all models to account for possible within-participant effects. Thus, Set 1 included this control variable, as well as the same set of predictors as previously described, in a multiple linear regression: the standard covariates (BMI, sex, physical activity), baseline RSA, and vagal withdrawal (VW). This model was significant, $R^2 = .292$, $F(6, 66) = 4.540$, $p = .001$. Parameter estimates are shown in Table 9. Specifically, there was a significant effect of vagal withdrawal, but in the opposite direction as predicted: Those who exhibited *less* vagal withdrawal were perceived as more compassionate during the Expressed Compassion message. There were also significant effects for participant sex (females rated as more compassionate) and BMI (inversely related to perceived compassion). Set 2 included the ratings of Control messages, the standard covariates, baseline RSA, and vagal elevation (VE). This model was also significant $R^2 = .244$, $F(6, 66) = 3.548$, $p = .004$. However, here, there was only a trend for vagal elevation in the predicted direction. As shown in Table 9, greater vagal elevation was associated with greater perceived compassion. The model for Set 3 tested the effect of vagal flexibility sum, and no significant effects of RSA measures were found.

Method C: Does vagal functioning predict linguistic content of compassion messages?

Linguistic characteristics. Transcribed Expressed Compassion messages were analyzed for word content and summarized in Table 10; because most of the variables exhibited skewness, non-parametric descriptive statistics are shown. Messages were on average about 117 words long, although there was substantial variability, with messages ranging from 33 to 291 words; the vast majority of words used were found in the LIWC dictionaries. On average, one category of words—Social Processes—composed about 17% of each message. This broad category includes all personal pronouns (except 1^{st}-person singular) and words that involve social interaction (e.g., “talking,” “sharing”), as well as words specific to different kinds of relationships. Furthermore, the category Affiliation (e.g., “ally,” “friend”), which only composed 2.5% of messages, on average, is a distinct dictionary (i.e., not nested within Social Processes) that relates to the drive to affiliate with others. These two categories—Social Processes and Affiliation—were highly correlated (r = .72, p < .001), so an index variable, *Social Focus,* was calculated as the mean of the Social Processes and Affiliation categories.[11] This *Social Focus* index was significantly correlated with perceived suffering and self-reported compassion, such that more socially-focused language was used when the participant felt more compassion (r = .27, p = .016) and when the recipient’s suffering was more extreme (r = .30, p = .007). This index offers convergent validity that participants’ messages of Expressed Compassion were, indeed, related to how much compassion they felt. Although positive emotion words and negative emotion words only represented a small portion of words (5% and 2%, respectively), they exhibited different distribution patterns. Nearly all

[11] The index variable was log-transformed in analyses to meet normality assumptions.

participants (98%) used positive emotion words to some extent, compared to 82% of participants who used negative emotion words. Within the negative emotion category, 46% of participants used sad words; 27% used words in the Anxiety sub-category; only 19% of participant used words related to anger. Participant sex was uncorrelated with Social Focus or any emotion category.

The effect of vagal function on socially-focused language. To test the effect of RSA measures on socially-focused language, using Sets 1 – 3, each multiple linear regression was conducted with Social Focus (log-transformed) as the dependent variable; standard covariates (sex, BMI, physical activity) and baseline RSA were predictors in all models. Set 1 included vagal withdrawal (VW); Set 2 included vagal elevation (VE); and Set 3 included vagal flexibility sum (VF-sum). Models using Sets 1 – 3 were not overall significant (all ps > .378). Moreover, no significant effects were found for any of the RSA measures on the Social Focus index.

The effect of vagal function on positive emotion words. The effect of vagal activity on positive emotion words was tested in the same manner as described above, using the percent of positive emotion words as the dependent variable (transformed to have normal distribution). Again, models from Sets 1 – 3 were not overall significant (all ps > .861), and there were no significant effects of any of the RSA measures on use of positive emotion words.

The effect of vagal function on stress vulnerability. Stress vulnerability was operationalized as the anxiety-related words (e.g., “worried”) used in the compassion messages. Because a considerable proportion of participants did not use any anxiety words, the dependent variable was transformed into a binary outcome (0 = no anxiety words; 1 = anxiety words present). Logistic regressions were used to calculate the effect of vagal activity on the probability of using anxiety words, although the same Sets 1 – 3 were used, as described above. The model with Set 1 (Nagelkerke's R^2 = .300) revealed a significant effect of vagal withdrawal opposite of the predicted direction, as shown in Table 11; greater vagal withdrawal significantly predicted a higher likelihood of using anxiety-related words when expressing compassion. The model with Set 2 did not show any significant results, but the model with Set 3 (Nagelkerke's R^2 = .217) also found a significant effect of VF-sum, such that higher vagal flexibility was related to a greater likelihood of using anxiety-related words (see Table 11).

Exploratory Analyses

Quadratic relationship between baseline RSA and self-reported compassion. Previous work has shown that there may exist a quadratic relationship between baseline RSA and prosocial behavior, such that higher baseline RSA is predictive of these outcomes up to a certain point, but more extreme levels of baseline RSA may actually have harmful consequences (Kogan et al., 2014). Germane to the current investigation, Kogan and colleagues found that there was a quadratic relationship between baseline RSA and prosocial positive emotions, specifically compassion and gratitude. Thus, my one-item self-report measure of compassion towards the participant's message recipient served as the dependent variable, with baseline RSA, its quadratic term, and the standard covariates (sex, BMI, physical activity) as predictors in a stepwise multiple linear regression. Because the reported relationship in prior research is specific to baseline RSA, and not changes in RSA, I did not include any measures of vagal flexibility in this model. First, to determine the unique effect of the quadratic term, all predictors except the quadratic RSA term were included, and the overall model (including the effect of baseline RSA) was not significant. However, adding the quadratic baseline RSA term led to a significant improvement in model fit: $\Delta R^2 = .133$, $p =$

.001. Thus, the full model with the quadratic RSA term, baseline RSA, and standard covariates was significant, $R^2 = .221$, $F(5, 73) = 4.151$, $p = .002$. Specifically, the effect of baseline RSA became significant in the predicted direction ($B = 3.416$, 95% CI [1.500, 5.332], $p = .001$), such that higher baseline RSA predicted experiencing greater compassion. The quadratic term was also significant ($B = -0.268$, 95% CI [-0.419, -0.117], $p = .001$), replicating Kogan et al.'s findings that moderate baseline vagal activity may be optimal for prosocial outcomes. These significant relationships remained after controlling for the reported severity of the message recipient's suffering. Figure 4 (left panel) shows this quadratic equation plotted against actual data points.

These intriguing findings led me to test whether a quadratic baseline RSA term may explain the Expressed Compassion variables of interest. Thus, I tested all outcome variables with the following covariates: baseline RSA, quadratic RSA term, and the standard covariates. For pitch cues and intensity cues, multivariate tests revealed no significant effect of this quadratic relationship. Likewise, listener-perceived compassion ratings, positive emotion words, and anxiety-words were also not quadratically related to baseline RSA. However, I did find a significant quadratic relationship between baseline RSA and the use of socially-focused language, in the predicted direction: baseline RSA positively predicted the amount of socially-focused words during Expressed Compassion ($B = 0.805$, 95% CI [0.237, 1.373], $p = .006$), but predicted less use of socially-focused language when baseline RSA is especially low or especially high (quadratic term $B = -0.063$, 95% CI [-0.108, -0.018], $p = .006$). This relationship is depicted in Figure 4 (right panel).[12]

[12] Although parameter estimates were significant, the overall model is at the level of a trend, $F(5, 69) = 2.233$, $p = .060$.

Enacted compassion. One exploratory variable measured "enacted compassion"—that is, whether the participant indicated that they would like a copy of his or her webcam recording to send to the suffering loved one. Out of the 85 participants in my sample, only six participants indicated they wanted the recording. I had no a priori estimations of the frequency of this event. A series of *t*-tests were conducted, comparing those who took the recording to those who did not. No significant differences emerged between the two groups in participant sex or any measure of vagal activity (baseline, withdrawal, elevation or flexibility).

Discussion

In this study I took a multi-method approach to investigate the relationship between cardiac vagal activity and expressions of compassion. I had two primary aims: first, I sought to establish the validity of my expanded conceptualization of vagal flexibility, which included tonic levels of cardiac vagal activity (i.e., baseline RSA), reductions in vagal activity during an attention task ("vagal withdrawal," measured as RSA reactivity), and increases in RSA during a guided meditation ("vagal elevation," measured as RSA reactivity). Indeed, I found that, on average, the visual attention task and meditation task were effective at changing RSA activity in the intended direction (mean decrease during attention task, mean increase during meditation), but that these indices of vagal withdrawal and elevation were inversely correlated, an unexpected result. In my second aim, I sought to use several different methods to quantify expressed compassion by examining changes in prosody, subjective perceptions of compassion, and linguistic content. For instance, I extracted pitch and intensity parameters from vocalizations to investigate how prosody changed from the control message to the Expressed Compassion message. When expressing compassion, I found that participants' exhibited lower levels of pitch, pitch range, intensity, less intensity variability, and intensity range, compared to control. Although no studies to my knowledge have previously examined prosody of compassion, these findings are consistent with expressions of love/tenderness and sadness (Juslin & Laukka, 2003). Aside from this pattern, most of the variables from one method of assessing expressed compassion were not correlated with variables from the other methods. However, listener-perceived compassion of content-filtered messages was positively associated with the use of socially-focused language, and critically, the use of socially-focused language was itself related to self-reported compassion. This provides some evidence that two of the three methods (listener perceived compassion and linguistic content) related to the face-valid measure of self-reported compassion.

Finally, I used the expanded definition of vagal flexibility to investigate whether and to what extent it predicted nonverbal and linguistic properties of Expressed Compassion messages. To test whether vagal flexibility was most predictive when it was derived from only one context or across all multiple contexts, I ran models that tested the influence of vagal withdrawal, vagal elevation, and vagal flexibility, respectively, for each primary outcome variable. I found that vagal functioning was not related to changes in any pitch parameters. Likewise, vagal elevation and vagal flexibility (sum score) were not related to changes in intensity parameters. Notably, however, there was some evidence that baseline RSA significantly predicted a greater reduction in intensity mean, which supported the hypothesis that vagal functioning predicts heightened prosodic cues (Table 8, Set 1). By contrast, there were several effects that were opposite of the predicted direction: higher baseline RSA (Table 8, Set 2) and greater vagal withdrawal (Table 8, Set 1) predicted expanded intensity variability and intensity range, respectively. All patterns reported for intensity cues should be interpreted with caution, however, as none of the individual regression models reached significance.

Second, I content-filtered control and expressed compassion messages so that no words could be deciphered, and recruited a sample of online participants ("MTurk listeners") to rate these content-filtered messages for perceived compassion. Controlling for within-participant effects, I found a significant effect for the vagal withdrawal model, but in an unexpected direction. The greater the *increase* in RSA from baseline to attention task ("negative" vagal withdrawal), the greater the person's rating of perceived compassion. I found a similar effect (albeit marginally significant) of vagal elevation in the predicted direction, such that boosts in RSA during meditation predicted greater perceived compassion. The model of vagal flexibility was not related to perceived compassion.

In my third approach, I investigated the linguistic content of expressed compassion messages to test whether and to what extent RSA activity predicted language that is theoretically associated with greater RSA activity: more socially-focused language, more positive emotion words, and fewer anxiety-related words. Across the three statistical models, I did not find that RSA activity had an influence on socially-focused words or positive emotion words. However, a significant effect of vagal withdrawal emerged opposite of the predicted direction, such that greater vagal withdrawal was associated with a greater likelihood of using anxiety-related words (Table 11, Set 1); this finding was present in the vagal flexibility model (sum score) as well, also opposite of the predicted direction (i.e., greater flexibility was related to greater likelihood).

Finally, my exploratory analyses revealed that the relationship between baseline RSA and self-reported compassion (as well as the use of socially-focused language) was quadratic, which conceptually replicated previous work (Kogan et al., 2014). Moderate levels of baseline RSA predicted the greatest degree of self-reported compassion, whereas more extreme values of RSA (higher or lower) were related to lower self-reported compassion. This quadratic relationship remained when controlling for the severity of the message recipient's suffering. Whereas Kogan and colleagues measured self-reported compassion in a seven-item scale that assessed the extent to which one generally experiences that emotion, my measure targeted a specific feeling of compassion for another person whom the participant had identified as currently suffering. Kogan et al. (2014) also reported a quadratic relationship between baseline RSA and perceptions of prosociality (from a brief, silent video clip) of a person listening to another's suffering. In my study, I did not find a quadratic relationship between baseline RSA and listener-perceived compassion. However, there may be important differences between experiencing compassion subjectively and effectively conveying compassion in a message. In fact, my overall pattern of results—primary and exploratory—suggest that in many cases these processes diverge, with the exception of socially-focused language, which is indeed associated with self-reported compassion.

This is one of the first investigations to use vagal elevation (measured as change in RSA during meditation) by itself or in combination with other RSA measures as a potential biomarker of positive social outcomes. Moreover, drawing from theoretically-linked behaviors and anatomical structures (Porges, 2007; Porges, 2011), I targeted a unique pathway through which caretaking and affiliation behaviors are exhibited: the expression of compassion. This novel approach was used to examine the prosody, subjective listener perceptions, and linguistic content of compassionate messages, none of which have been previously used to examine compassion in non-scripted, naturalistic settings. Additionally, this is the first time that expressed compassion has been examined in the context of physiological activity.

Despite the potentially novel contributions of this study, overall my findings provide only weak support for the claim that vagal elevation uniquely predicts the qualities of expressed compassion; out of ten measured outcomes assessed by three different methods, greater vagal elevation only marginally predicted higher ratings of listener-perceived compassion. Given the large number of tests, this small finding was likely spurious. Indeed, it seems that the strongest predictor of expressed compassion was *vagal withdrawal* alone, although in the opposite direction than predicted. Decreases in RSA during the attention task (i.e., greater vagal withdrawal) were associated with dampened prosodic intensity cues, lower listener-perceived compassion, and greater likelihood of using anxiety-related words. I hypothesized the opposite pattern to be in line with Porges's theory that RSA is a marker of stress vulnerability and social engagement (Porges, 2001; Porges, 2011), and specifically because vagal withdrawal has been shown to be a marker of social sensitivity and altruistic behavior (Muhtadie et al., 2015; Bornemann et al., 2016), a finding that I failed to replicate. Furthermore, using a composite score of *vagal flexibility* seemed to obfuscate the individual effects of vagal withdrawal or vagal elevation. The inverse relationship observed between vagal withdrawal and vagal flexibility further suggested that a sum score of the two constructs may not be as useful as each alone, as it creates an index in which the effect of one is frequently dampened by the other.

However, existing evidence suggests that social sensitivity might not necessarily result in more positive social behaviors. For instance, in Study 4 of the paper by Muhtadie and colleagues (2015), people who exhibited greater vagal withdrawal exhibited less sociable behavior after receiving negative feedback, suggesting these individuals are more socially sensitive. Thus, it is possible that individuals who exhibit greater vagal withdrawal are hampered by their own sensitivity when expressing compassion: that is, the experience of considering another person's suffering may lead to negative affective processes that impede the effective portrayal of compassion (e.g., empathy-related personal distress; for review, see Eisenberg & Fabes, 1990). Furthermore, people whose capacity for vagal withdrawal is higher may be more vulnerable to experiencing stress, which may in turn be associated with a greater likelihood of using anxiety-related words when expressing compassion.

Alternatively, it may have been the case that the nature of the baseline and attention task differed across individuals. For this reason, among others, the utility and meaning of baseline cardiovascular activity has been debated (Jennings, Kamarck, Stewart, Eddy, & Johnson, 1992; Laborde, Mosley & Thayer, 2017). For instance, although on average participants' RSA decreased during the attention task, many participants' RSA actually increased or didn't appreciably change at all. It may be that, for some individuals (for instance, those high in neuroticism), a resting baseline required more vigilance or allowed rumination, so RSA activity during rest reflected different psychological states across individuals. Indeed, trait neuroticism was negatively correlated with baseline RSA ($r = -.256$, $p = .022$) as well as with RSA during the attention task ($r = -.245$, $p = .027$), not correlated with vagal withdrawal or RSA during meditation, yet positively associated with vagal elevation ($r = .310$, $p = .005$). This suggests that for these individuals, the baseline period was indeed more similar to a challenge context than to a safe context. Because the vagal withdrawal and vagal elevation scores are both derived from the resting baseline, baseline scores that are confounded with individual differences are likely to overestimate or underestimate these vagal flexibility measures. Consequently, I explored alternative metrics of vagal flexibility that would be robust to variability in baseline RSA, and they are summarized in Appendix E. Overall, these metrics produce mostly null results or mirror results presented here (with a few exceptions). However, all measures of RSA reported here and in the appendix reflect minute-by-minute temporal resolution; it is possible that a second-by-second rolling window may better capture the variability in RSA across different contexts.

In sum, although in this study I implemented an expanded assessment of vagal flexibility and novel measures of expressed compassion, support for my hypotheses was limited. Across all models for each outcome (a total of 30 univariate tests) in the primary analyses, only one supported my hypothesis that greater cardiac vagal function was related to expressed compassion; specifically, I found that baseline RSA significantly predicted intensity cues through dampened intensity mean. Five models showed effects opposite of the predicted directions: baseline RSA and vagal withdrawal were inversely associated with certain intensity cues; vagal withdrawal was associated with lower listener-perceived compassion; vagal withdrawal and sum vagal flexibility were associated with a greater likelihood of using anxiety-related words. The remaining 24 models showed null effects. Although it remains possible that my measures of vagal flexibility and expressed compassion are not reliable or valid, my results suggest that measures of vagal functioning do not reliably predict expressed compassion, which contradicts previously published work showing that measures of vagal flexibility predict measures of social sensitivity (Muhtadie et al., 2015) and prosocial behavior (Bornemann et al., 2016).

CHAPTER 4: GENERAL DISCUSSION

In the present research, I tested whether and to what extent measures of cardiac vagal activity influenced individual differences in social engagement behaviors, particularly in the domain of nonverbal behavior. First, I examined whether cardiac vagal tone predicted the degree to which people engaged in social affiliation behaviors, and whether conditions of perceived threat and perceived safety moderated this effect. Given the important role that context plays in shaping both physiology and behavior (as shown in Study 1), I then shifted the focus from how a measure of cardiac vagal tone shapes affiliative *behaviors* across different contexts (Study 1), to how measures of cardiac vagal activity *change* across different contexts, and whether and to what extent these changes differentially predicted social engagement behaviors (Study 2).

In Study 1, I tested whether cardiac vagal tone (CVT; measured as resting respiratory sinus arrhythmia or RSA) was associated with the degree to which people engaged in automatic facial mimicry across three different contexts (neutral, perceived threat, perceived safety). I reasoned that, because CVT is associated with a host of positive social outcomes, those with higher resting RSA would engage in relatively more mimicry, relative to those with lower resting RSA, across all contexts. Under neutral conditions, I did not find support for the hypothesis that higher RSA was associated with greater mimicry. Furthermore, there was a conflicting prediction as to whether a state of threat would enhance or inhibit facial mimicry: the polyvagal theory suggests that *less* social engagement behavior occurs under threat, whereas a large body of evidence in social psychology suggests that people tend to affiliate relatively *more* under threat. Overall, my results suggest that people do indeed mimic more under perceived threat, corroborating evidence from decades of work on affiliation motives (for a review, see Taylor & Lobel, 1989) and contradicting the polyvagal theory. Moreover, resting RSA significantly moderated this relationship. People with low RSA tended to mimic the same amount under threat and in neutral contexts; by contrast, people with average resting RSA mimicked more under threat, and this effect was even stronger for people with high RSA. I did not find evidence to support the hypothesis that perceived safety enhanced facial mimicry (or that RSA influenced this effect), although this null finding needs to be considered in light of evidence that the manipulation check of the safety condition failed.

Findings from Study 1 were noteworthy in two ways: first, they provided partial support for the polyvagal theory's claim that cardiac vagal tone influences social engagement behaviors, particularly those related to the striated muscles of the face (Porges, 2011). Principally, relative to low cardiac vagal tone (measured as resting RSA), higher cardiac vagal tone positively predicted increased spontaneous facial mimicry under perceived threat. However, resting RSA was not associated with facial mimicry in neutral or safe contexts. Furthermore, the main effect that perceived threat overall enhanced mimicry did *not* support the polyvagal theory's assertion that social engagement behaviors are dampened under perceived threat. Second, the findings of Study 1 contribute to the facial mimicry literature, showing conditions under which and people for whom automatic facial mimicry may be enhanced. Previous work has shown that a state of fear increases fear-congruent facial mimicry (Moody, McIntosh, Mann, & Weisser, 2007), but my findings are the first to show how threat increases *affiliative* facial mimicry, since the emotions mimicked—happiness and sadness—are not related to threat and are both emotional displays that invite affiliation, albeit in different ways. Furthermore, the moderation of this effect by CVT suggests that the propensity to engage in facial mimicry may be biologically based.

Interestingly, although the safety-induction seemed to be unsuccessful, there was a significant order effect of safety vs. threat on the type of mimicry. For participants who had already experienced the threat condition, mimicry of sad faces (but not happy faces) during the safety condition was relatively greater than for those still "naïve" to the threat condition (i.e., safety condition first). Although fear and sadness are different emotions, their valences are similar (i.e., negative), and both expressions usually involve the activation of the *corrugator supercilii* muscle (Lundqvist, 1995). With this in mind, I speculate post hoc that an emotion-congruence effect was found (Niedenthal, Brauer, Halberstadt, & Innes-Ker, 2001), such that participants in a negative mood from the previous threat induction mimicked valence-congruent facial expressions more than participants in a neutral or pleasant mood (i.e., had not yet experienced the highly-aversive threat-induction).

For Study 2, I was interested in how changes in cardiac vagal activity across multiple contexts—a term called "vagal flexibility"—differentially influenced social engagement behaviors. To complement my examination of automatic facial mimicry in Study 1, I targeted another affiliative behavior: the vocal expression of compassion. The polyvagal theory's social engagement system purportedly evolved to facilitate the social bonding and caretaking behaviors that occur between caretaker and infant (Porges, 2011). Such caretaking behaviors theoretically rely heavily on increased parasympathetic activation (Porges, 2011), so if vagal flexibility (and in particular, vagal elevation) is indeed a unique predictor of *enacted* prosocial behavior, its effects would be most likely found in these theoretically-proximal behaviors. Thus, instead of facial mimicry, I chose to study compassion in the context of vagal flexibility because compassionate expressions directly involve caretaking behaviors in the form of social support (Goetz, Keltner, & Simon-Thomas, 2010).

Furthermore, in Study 2 I sought to establish the validity of my expanded definition of vagal flexibility (which includes cardiac vagal activity in a challenge context, as well as in a safety context) and to replicate previous findings that vagal flexibility predicts empathic accuracy, as indexed by the Reading the Mind in the Eyes Test (Muhtadie et al., 2015). Although overall I successfully induced a state of vagal withdrawal (during challenge) and a state of vagal elevation (during safety), I was not able to replicate the previously established effect that vagal flexibility predicts empathic accuracy. My second aim was to quantify expressed compassion by measuring prosodic cues, subjective listener-perceptions of compassion, and linguistic content. A distinct pattern of prosodic cues specific to compassion (as opposed to control) emerged. Furthermore, the use of affiliative language was related to both listener-perceptions of compassion and participant self-reports of compassion, although none of these components was related prosodic cues. Finally, I tested whether and to what extent vagal flexibility predicted expressed compassion. Generally, with few exceptions, I did not find support for my hypothesis that vagal flexibility (as a combined index of vagal withdrawal and vagal elevation) was related to expressed compassion. Nevertheless, I found some evidence that cardiac vagal tone (not vagal flexibility) was associated with heightened prosodic cues when expressing compassion. Furthermore, vagal withdrawal, on its own, predicted relatively *lower* listener ratings of perceived compassion and *greater* use of anxiety-related words, each of which was opposite of the predicted direction.

Whereas the goal of much research on the vocal expression of emotion has been to find acoustic and subjective properties that map onto discrete emotional states (for a review, see

Juslin & Laukka, 2003), my aim was not to find parameters that were related to the emotional experience of compassion, although a clear pattern of overall lower pitch and lower intensity emerged. Rather than *which* properties are common to all compassionate expressions, I was interested in *how* individuals effectively express compassion and social support—a form of caretaking behavior—to a suffering relationship partner. Verbally expressed compassion may function in relationships in a manner that bears similarities to expressed gratitude. Expressing gratitude in relationships works not only by enhancing relationship maintenance behaviors (Lambert & Fincham, 2011), but the partner's perceived responsiveness of the gratitude expression has important consequences for relationship satisfaction as well (Algoe, Haidt, & Gable, 2008). Likewise, expressing compassion may strengthen relationships by conveying investment in the other's wellbeing for his/her own sake, a key feature of love (Hegi & Bergner, 2010). Furthermore, it may serve as a signal that the expresser is sensitive to the relationship partner's needs, a critical element in forming intimate relationships (Reis, Clark, & Holmes, 2004). Because humans have evolved to live in groups (Brown & Brown, 2006), being perceived as a more valuable relationship partner serves a clear evolutionary function, as well as a psychosocial one. Although evidence from Study 2 is mixed, it is possible that vagal functioning—whether tonic levels or indices of flexible change—may influence the ability to express compassion, which is likely to have downstream consequences for relationship quality and maintenance.

Are the modest observed effects of vagal activity on expressed compassion due to greater social sensitivity (i.e., greater awareness of social information) or a greater capacity to engage in social affiliative behaviors? The effective communication of compassion necessarily involves both components, as it is important to be sensitive to another's emotional state, as well as to be able to convey one's personal emotional state in an appropriate manner. These two sources of variability may even exist in the voice. For instance, Scherer (1995) has classified psychological influences on the voice in two forms, "push" and "pull" effects. Push effects arise from physiological changes that affect the vocal production mechanisms; for example, arousal influences respiration rate and tension of laryngeal muscles, resulting in higher-pitched, more rapid speech. Pull effects, on the other hand, originate from the individual's external conditions that influence the voice; for example, self-presentation motives to convey dominance may alter the pitch or intensity of the voice. Expressing compassion, then, likely involves both push and pull effects: push effects arising from the individual's emotional experience, and pull effects resulting from the individual's motivation to convey emotional support. These two sources of variability are not possible to disentangle in this study, and are problematic to extricate in everyday life more generally (Juslin & Scherer, 2008).

If vagal withdrawal is indeed a marker of social sensitivity (as described in Muhtadie et al., 2015), it may *not* be a marker for the capacity to socially engage. In fact, my results suggest that social sensitivity may be counterproductive to the goal of expressing compassion, since people with greater vagal withdrawal were actually perceived by listeners as *less* compassionate. However, these listener-perceptions were based on content-filtered recordings, so it is possible that people who have greater vagal withdrawal (and social sensitivity) do not convey compassion as effectively through tone of voice, yet their words reflect greater sensitivity to the other's suffering. Indeed, although contradictory to my hypothesis, vagal withdrawal predicted a greater likelihood of using anxiety-related words (e.g., "worried"). Thus, I speculate post hoc that socially-sensitive individuals are more susceptible to the "push" effects mentioned above; their compassion, manifested as anxiety or worry, may result in a higher-arousal vocal state that is perceived as less compassionate. By contrast, although not directly related to vagal flexibility, individuals with higher baseline RSA exhibited heightened prosodic cues during the compassionate messages (e.g., greater reductions in intensity); I speculate that these individuals may exhibit greater "pull" effects, manifested as a greater motivation to change their voice in order to effectively convey compassion. Unfortunately, the design of my study did not allow me to explore other modalities through which compassion is conveyed, particularly the use of touch. In fact, touch may be one of most powerful nonverbal methods of communication compassion, as soothing touch has been found to downregulate cortisol levels (Francis & Meaney, 1999) and downregulate stress-related areas of the brain (Coan, Schaefer, & Davidson, 2006). Because vocal expression is only one method people use to communicate emotion, it is possible that vagal activity influences modalities beyond those which were captured here.

There are several limitations of Study 2. First of all, participants were asked to record a message to somebody who was not present. Thus, experimental demand or the artificiality of the procedure may have altered the nature of the expressed compassion task; more genuine compassion likely requires spontaneity and the presence of the message recipient, which was not possible to achieve here. As another study limitation, the primary dependent variables (acoustic properties, subjective listener ratings, and linguistic analysis of messages) have never been used in this particular context, so extra caution must be taken when making generalizations about the meaning of the results. Nevertheless, I found a clear pattern of reduced pitch and reduced intensity when expressing compassion, relative to control, and I found that one linguistic cue (socially-focused language) correlated with listener-perceived compassion and self-reported compassion. Taken together, there is some evidence that two of the methods used (listener perceptions and linguistic analysis) converge. Ideally, structural equation modeling that employs a bi-factor model could more definitively show how and to what extent these measures map onto the latent construct of Expressed Compassion. Continued use of these measures in different contexts will be critical to further establish their reliability and external validity. Finally, given the correlational nature of the study design, causal relationships between physiological traits and psychological outcomes cannot be determined. For instance, there is evidence that the relationship between RSA and psychosocial wellbeing is reciprocal (Kok & Fredrickson, 2010), so it is not clear if RSA underlies the capacity to express compassion, resulting in heightened linguistic and paralinguistic cues, or if a separate psychological process (e.g., social sensitivity, empathic ability) enhances social information, enabling more effective social engagement behaviors and—over time—greater RSA activity.

It is worth noting that there are several other theories aside from the polyvagal theory that attempt to explain the relationship between cardiac vagal activity and psychological phenomena, although they are not as applicable to the research question currently investigated. For one, the neurovisceral integration model hinges on the relationship between the autonomic nervous system and the prefrontal cortex, such that greater cardiac vagal tone is a biomarker of greater executive function (Thayer et al., 2009). The studies presented here do not measure neural activity, but one finding in Study 2—baseline RSA was positively associated with vagal withdrawal—suggests that, during a task that requires executive control, people with higher vagal tone may be better able to shift autonomic activity to meet the demands of the situation, a pattern consistent with the neurovisceral integration model. Another model, the biological behavior model proposed by Grossman and Taylor (2007), argues that RSA and cardiac vagal tone are dissociable, and that it is *phasic* shifts in RSA (not tonic measures) that may predict an organism's ability to meet the metabolic demands of various situations. Following this theory's claim, my measures in Study 2 that capture RSA change (e.g., vagal withdrawal) would be markers of optimal biobehavioral function. However, my findings that vagal withdrawal predicted *worse* outcomes of expressed compassion do not seem to provide support for this theory.

Furthermore, although my studies draw heavily from the polyvagal theory, the theory is not without its limitations or criticisms. Other scholars have criticized Porges's phylogenetic claim that cardiac vagal control evolved first in mammals, and further argue that resting RSA does not necessarily measure cardiac vagal tone (Grossman & Taylor, 2007). Moreover, the polyvagal theory draws heavily from anatomy and developmental psychology, which at times limits its generalizability to nonclinical adult populations. For instance, much of Porges's evidence that cardiac vagal tone is linked to social engagement behaviors, in particular vocal prosody, is drawn from studies on neonates and clinical adult populations (Porges, 2011, chapter 13). Furthermore, his claim that "social communication is determined by the cortical regulation of medullary nuclei via corticobulbar pathways" (Porges, 2011, p. 170), is greatly oversimplified. Undoubtedly, the cortex plays a role in social communication, but it can do this through regulating numerous other neural and anatomical structures that in turn influence behaviors in the social engagement system (e.g., facial expression of emotion).

Future Directions

Aside from the potential drawbacks of the polyvagal theory and measurement of RSA, there are a variety of other potential hypotheses that could be tested in the data collected in Study 1. For instance, the facial stimuli used in the face viewing task represented a racially diverse set of faces. Multilevel modeling could be used to test whether there were any interactions between face race and mimicry. Previous work has shown that behavioral mimicry is reduced when the person being mimicked is an out-group member (e.g., Van der Schalk et al., 2011; Yabar, Johnston, Miles, & Peace, 2006), so it is possible that a race effect would emerge, such that white participants exhibit less facial mimicry towards out-group (non-white) members. Interactions between race and condition could be examined as well. In addition, the memory task, which was originally employed as part of the cover story, could be used to test how perceived threat or perceived safety influenced memory for the faces presented, and whether cardiac vagal tone, degree of facial mimicry, or emotion valence (happy vs. sad) predicted participants' accuracy. Beyond the potential research questions that could be studied within this dataset, findings from this study open up several potentially interesting avenues for future research. For instance, under threat, does cardiac vagal tone also enhance mimicry toward hostile or angry faces? The emotional displays used in Study 1, happiness and sadness, are generally seen as relationship-enhancing (Hess & Fischer, 2013). However, it could be tested whether CVT only selectively predicts threat-enhanced facial mimicry to affiliative emotional displays, or if it it predicts threat-enhanced facial mimicry across multiple types of facial expressions, including hostile ones. Furthermore, can the effect of threat-enhanced mimicry, and its moderation by resting RSA, be generalized to other domains of behavioral mimicry? For instance, after a threat induction, individuals with higher vagal tone may more likely to mimic another person's body movement, and this in turn may prospectively influence liking.

The findings of Study 2 suggest new directions for future research in nonverbal behavior, emotion, and relationships. First of all, within the existing dataset, participants' messages contained a visual component not considered here, so future investigations could explore the emotional cues of participants' facial expressions while recording messages. In addition, prosodic cues of vocalizations have largely been utilized to study the vocal encoding of emotion, decoding accuracy, or emotion recognition (for a review, see Scherer, 2003), but this study lays the groundwork for subsequent investigations that may utilize prosodic cues in other contexts, such as perceived responsiveness in relationships. Although I had independent raters listen to content-filtered messages, this is merely a distal evaluation of the expresser, and does not capture the language and nuances that the message receiver would detect and understand. Partner responsiveness is shown to be important in both romantic and platonic relationships (Reis & Gable, 2015). Future studies, in which compassion is expressed during dyadic interactions, will be an important next step to further unpack the relationships between expressed compassion and physiology observed here.

Conclusion

Social affiliation is a drive that is intractably rooted in the human experience. Beyond people's initial motivation to form positive relationships with others, humans have also evolved to maintain relationships that foretell numerous beneficial mental and physical health outcomes (Holt-Lunstad, Smith, & Layton, 2010). Because affiliation is critical to the survival the species, humans have necessarily evolved biological systems that underpin the capacity to socially engage with others. Although the complete understanding of all biological processes that contribute to social affiliation cannot be known at this point, studying candidate systems, such as parasympathetic nervous system activity, is a useful avenue to better understand how such complex processes may be related to social engagement.

Through the lens of nonverbal behavior, I investigated how cardiac vagal activity (measured as RSA across various contexts) predicted social engagement. My results suggest that people engage in relatively greater automatic facial mimicry when under perceived threat. Thus, in the face of danger, humans automatically engage in greater affiliative behaviors, but this depends on the individual's tonic levels of cardiac vagal activity. Individuals who have higher tonic levels of RSA engaged in even greater levels of facial mimicry, whereas those with lower tonic RSA did not. This suggests that people who have greater biological resources may be better able to—in part through facial mimicry—gather social information (e.g., aiding perspective-taking, ascertaining the meaning of another's smile; Hawk, Fischer, & van Kleef, 2011; Niedenthal, Mermillod, Maringer, & Hess, 2010) and build social resources (e.g., through increased likability, Yabar & Hess, 2007), which sets themselves up to be more resilient when faced with threat.

Furthermore, in my second study, I found that tonic RSA was associated with heightened prosodic cues when expressing compassion. Again, individuals who possessed higher levels of this biological resource may, through conveying emotional support and compassion, be better able to effectively signal their investment in and value to a relationship partner, enabling the strengthening and maintenance of high-quality relationships. Conversely, individuals who exhibited greater vagal withdrawal (i.e., decreased RSA in a challenge context) may be disadvantaged when expressing compassion, which was contrary to my hypotheses. These individuals were perceived as less compassionate by untrained listeners and were more likely to use anxiety-related language. I did not find any effects of vagal elevation (i.e., the capacity to increase RSA under perceived safety), either singly or combined with other measures of vagal flexibility, on measures of expressed compassion. Overall, the present research provides some evidence that the capacity to engage in affiliative, nonverbal behaviors depends in part on individual differences in cardiac vagal control.

APPENDIX A: STUDY 1 AND STUDY 2 QUESTIONNAIRES

Presented below (in alphabetical order) are descriptions of the questionnaires administered in Study 1 and Study 2. Measures with a "1" superscript were used in Study 1; measures with a "2" superscript were used in Study 2.

Affect Grid[1]

A 9-by-9 square grid was shown to participants to assess core affect (Russell, Weiss, & Mendelsohn, 1989). Participants were instructed to select a place on the grid that described how they currently felt at the moment, within two dimensions: arousal (described as "high energy" to "low energy" in instructions, along the y-axis) and valence (described as "unpleasant mood" to "pleasant mood" in instructions, along the x-axis). This scale was included in Study 1 for exploratory purposes not investigated here.

Attachment Style[1]

The 18-item revised Adult Attachment Style (AAS; Collins, 1996) measure was administered to assess attachment style in relationships generally. Participants indicated using a 5-point scale the degree to which they felt a statement was characteristic of themselves (e.g., "I find it relatively easy to get close to people;" 1 = "Not at all characteristic of me" to 5 = "Very characteristic of me"). The scale comprises three subscales, each of which describes a particular attachment dimension: comfort with closeness/intimacy, feeling that one can depend on others, and anxiety of rejection. After reverse-scoring particular items according to standard procedures, the average of the six items was computed for each subscale. This scale was included in Study 1 for exploratory purposes not investigated here.

Demographics[1,2]

Participants were asked their age, gender, place of birth, and where they grew up. Study 1 demographics also asked about ethnicity, race, English-language status, and family income. For Study 2, this additional demographic information (in addition to biological sex) was obtained through prescreening questionnaires on the participant pool website.

Empathic Accuracy[1,2]

The Reading the Mind the Eyes Test (RMET; Baron-Cohen, Wheelwright, Hill, Raste, & Plumb, 2001) was used to test the accuracy of participants' detection of the emotional states of others. Participants were presented with 36 black-and-white photographs of people's eye regions. From a selection of four emotion words (e.g., playful, comforting, irritated, bored), participants were asked to select the word that most closely matched how the photographed person might be feeling. Higher scores are indicative of greater empathic accuracy. This scale was included in Study 1 for exploratory purposes not investigated here. In Study 2, the RMET was used in several analyses; see "Results" section of Study 2.

Giving Emotional Support (GES)[2]

A modified, five-item GES subscale of the two-way Social Support Scale (Shakespeare-Finch & Obst, 2011) was used to assess the degree to which participants provided emotional support to three of the people they had named in the Naming Task in Study 2. The scale typically assesses general emotional support, but here it was modified to be specific to a particular person. Piped text was used to that only names (not relationship types) were presented. Participants indicated the degree to which each statement (e.g., "I am there to listen to this person's problems") was true for them, from 0 ("Not at all") to 4 ("Always"). The GES was assessed for three relationships: between the participant and whom they had named during the Suffering, Admire, and Appreciate Naming Task. This scale was included in Study 2 for exploratory purposes not investigated here.

Group Entitativity[1,2]

To assess the degree to which participants felt intertwined with the people in their everyday lives, six different pictures were presented (Gaertner & Schopler, 1998). Each contained a circle labeled "self" and was surrounded by three other circles (representing other people) in varying degrees of closeness. Participants were asked to select which picture most closely represented how they connected they felt in relation to others. This scale was included in both studies for exploratory purposes not investigated here.

Inclusion of Others in Self (IOS)[2]

The IOS (Aron, Aron, & Smollan, 1992) assessed self-other overlap by presenting a series of graphics. Each graphic contained two circles, one of which represented the self, and the other represented another person. For each relationship described during the Naming Task of Study 2, participants were asked to select which graphic best described their current relationship with that person. Piped text (e.g., names that participants had provided) was used so that relationship types (e.g., "the person you envy") were not presented, only names. For example, if a participant named *John* as someone he or she admired, the instructions would read, *Think about the person you named John.* This scale was included in Study 2 for exploratory purposes not investigated here.

Loneliness[1]

The UCLA Loneliness Scale (Russell, 1996) is a 20-item questionnaire that assesses perceived loneliness. Participants responded on a 4-point scale (from "I often feel this way" [scored as 3] to "I never feel this way" [scored as 0]) the frequency with which they felt each statement was descriptive of them (e.g., “I have nobody to talk to”). Several items were reverse-scored. The sum of all twenty items was computed to calculate a loneliness score for each participant. This scale was included in Study 1 for exploratory purposes not investigated here.

Personality[1,2]

The Ten-Item Personality Inventory (TIPI; Gosling, Rentfrow, & Swann, 2003) assesses the Big Five personality traits (i.e., openness to experience, conscientiousness, extraversion, agreeableness, neuroticism). Participants were asked to rate how much a specific personality trait (e.g., “Extraverted, enthusiastic”) applied to them on a 7-point Likert-type scale (1 = “Strongly disagree”; 7 = “Strongly agree”). Five items were reverse-scored, and each of the five personality traits were calculated by taking the mean of the two corresponding scale items. This was assessed before the resting periods for both studies.

Physical Activity[1,2]

The International Physical Activity Questionnaire (short-form) (Craig et al., 2003), administered before the baseline, was used to assess participants’ level of physical activity in the past seven days. From this questionnaire, a physical activity index was calculated in accordance with published guidelines (World Health Organization, 2001) by summing the minutes per week of physical activity, weighted by vigor of activity. These health measures were included as control variables because body mass index and physical activity are correlated with RSA (Andrew et al., 2013).

Prioritizing Positivity (PriPos)[1,2]

This 6-item scale (Catalino, Algoe, & Fredrickson, 2014) was administered to assess the degree to which participants prioritized the experience of positive emotions in their lives.

The questionnaire asked participants to rate the degree to which they agreed with each statement (e.g., “A priority for me is experiencing happiness in everyday life.”) on a 9-point scale (1 = “Disagree strongly;” 9 = “Agree strongly”). This scale was included in both studies for exploratory purposes not investigated here.

Social Approach and Avoidance Motives[1,2]

An eight-item scale (Impett, Strachman, Finkel, & Gable, 2008) was used to assess individuals’ approach-oriented or avoidance-oriented motives in social relationships. Participants rated the degree to which each statement was true for their typical goals for friendships on a 7-point Likert-type scale (1 = “Not at all true of me”; 7 = “Very true of me”). Four items related to approach motives (e.g., “…move toward growth and development in my friendships.”), and four items related to avoidance motives (e.g., “…avoid disagreements and conflicts with my friends.”). Following standard procedures for using this scale, scores on approach items were averaged, and scores on avoidance items were averaged for two separate indices of social approach vs. avoidance motives. This scale was included in both studies for exploratory purposes not investigated here.

Subthreshold Autism Trait Questionnaire (SATQ)[1]

The SATQ is a five subscale, 24-item scale designed to assess non-clinical (subthreshold) autistic traits in the general population (Kanne, Wang, & Christ, 2012). For this study, only the Reading Facial Expressions (three items) and Social Interaction (eight items) subscales were administered. Participants were asked to indicate the degree to which they felt each statement applied to them (e.g., “I make eye contact when talking to others”), using a 4-point scale (0 = “False”; 3 = “Very true”). Following published guidelines, the mean rating for each subscale were computed to obtain SATQ subscale scores. This scale was included in Study 1 for exploratory purposes not investigated here.

APPENDIX B: STUDY 1 FACE STIMULI

Stimuli Selection

Twenty actors' faces were used from the IASLab Face Set[13], and 16 actors' faces were used from the MacBrain Face Stimulus Set ("NimStim")[14]. Because the faces were used as dynamic stimuli, both the neutral (close-mouthed) and emotional expressions were utilized to create the animated morphs. For faces in the IASLab Face Set, actors whose neutral expression accuracy rates were < 60% were eliminated, and emotional faces with an accuracy rate of < 60% were also excluded. To obtain enough faces in the final set, for faces in the MacBrain Face Stimulus Set, actors whose neutral expression accuracy was < 50% were excluded. The final set comprised 18 females and 18 males, half expressing happiness and half expressing sadness. In addition, I included actors from various races and ethnicities, including white, black, Asian, and Hispanic identities.

Stimuli Presentation

A total of 36 dynamic facial expression stimuli were used as stimuli for Study 1. Each stimulus began with the actor in a neutral expression, which then morphed to the emotional expression, and then morphed back to the neutral expression; stimuli were created with morphing software and then converted to movie files (FantaMorph 5, Abrasoft). The total duration of each stimulus was 3.6 seconds (see Table B1).

[13]Development of the Interdisciplinary Affective Science Laboratory (IASLab) Face Set was supported by the National Institutes of Health Director's Pioneer Award (DP1OD003312) to Lisa Feldman Barrett. More information is available on-line at www.affective-science.org.

[14]Development of the MacBrain Face Stimulus Set was overseen by Nim Tottenham and supported by the John D. and Catherine T. MacArthur Foundation Research Network on Early Experience and Brain Development. Please contact Nim Tottenham at tott0006@tc.umn.edu for more information concerning the stimulus set.

Stimuli presentation was divided up into three blocks of 12 faces each. Each block contained equal numbers of happy faces and sad faces, as well as an equal number of male faces and female faces. Faces within each block were randomized, and block order was counterbalanced across participants.

APPENDIX C: STUDY 1 SOUND STIMULI

Stimuli Selection

Sounds from IADS-2 are pre-rated on the dimensions of arousal, pleasure, and dominance (Bradley & Lang, 2007). For the Safety condition, I selected 20 sounds that were lower on arousal, high on pleasure, and higher on dominance. Ten sounds were social, and ten sounds were non-social. For the Threat condition, I selected 20 sounds that were high on arousal, low on pleasure, and low on dominance. Again, ten sounds were considered social (i.e. had human vocalizations), and ten were non-social (no voices). Descriptive statistics of the selected sounds are shown in Table C1. Once selected, the sounds were randomized and compiled into one sound file. Each sound lasted 6 seconds, with 1 second between sounds, for a total runtime of about 2 minutes, 40 seconds for the Safety sound set and the Threat sound set, respectively.

Pre-testing Sound Sets

Participants and Procedure

A sample of 90 participants from Amazon Mechanical Turk was recruited to listen to either the Safety sounds or the Threat sounds. After listening to the track, they completed two attention checks and were then asked to explicitly rate on a 5-point scale (1 = "Strongly Disagree"; 5 = "Strongly Agree") the degree to which they agreed with the following statements: 1) The sounds made me feel threatened/unsafe; 2) The sounds made me feel peaceful/safe; 3) The sounds made me laugh. The last question was included to ensure that the Threat sounds were indeed threatening and not perceived as comedic or bizarre.

Analyses and Results

Participants who did not pass both attention checks or who did not listen to the entire sound clip were eliminated from analyses, yielding a final sample of 84 participants. A series of *t*-tests were conducted to test whether the sound sets were indeed rated as threatening or safe. Participants in the Safety condition found the sounds significantly more peaceful and safe ($M = 3.93$) than those in the Threat condition ($M = 1.29$), $p < .001$. Conversely, participants in the Threat condition found the sounds significantly more threatening ($M = 3.56$) than those in the Safety condition ($M = 1.37$), $p < .001$. Finally, there was a significant difference between conditions in ratings of laughter, but it was such that people in the Safety condition agreed more strongly that the sounds made them laugh ($M = 3.30$) than those in the Threat condition ($M = 1.66$), $p < .001$. The relatively low ratings of laughter in the Threat condition was evidence that, by and large, the sounds were unpleasant and not particularly amusing. Thus, the sound sets presented in the pre-testing sample were included in Study 1.

APPENDIX D: STUDY 1 ALTERNATIVE ANALYSES

Results reported below reflect a different metric for analyzing EMG. Instead of standardized difference scores, percent change scores (relative to resting assessment or relative to Control condition) were used. Overall, the pattern of results reflects the main analyses reported; with a few exceptions. Here, I did not find a significant main effect of emotion type on eliciting differentiable zygomaticus major activity. Otherwise, like the main analyses, I found support for Hypothesis 3B, but I did not find support for Hypothesis 1, Hypothesis 2, or Hypothesis 3A. For all models for which sphericity assumptions are violated, the Greenhouse-Geisser correction for degrees of freedom and *p*-value is reported.

Manipulation Check: Happy vs. Sad Faces

Before testing the main hypotheses, I verified that stimuli elicited a response of facial mimicry under neutral conditions: specifically, greater activity (i.e., greater percent difference score) of the *orbicularis oculi (*OO) and *zygomaticus major* (ZM) in response to happy faces, and greater activity of the *corrugator supercilii* (CS) in response to sad faces. First, EMG data were transformed by dividing raw EMG activity during viewing each face (in Control condition) by raw EMG activity during the resting assessments (de Wied, van Boxtel, Matthys, & Meeus, 2012). These percent scores were then averaged across each emotion type (happy faces, sad faces) and within each muscle group. A repeated-measures general linear model or RM-ANOVA was conducted with muscle site and emotion type as within-subject factors. There was a main effect of muscle, $F(1.694, 125.390)$, and as predicted, there was a significant interaction between muscle site and emotion type, $F(1.161, 85.892) = 7.460$, $p = .005$. Pairwise comparisons with Bonferroni adjustment revealed that there was significantly more activity in the CS muscle during sad faces than happy faces ($M_{\text{sad}} = 1.353$, $SD = 0.067$; $M_{happy} = 1.206$,

$SD = 0.057$; $p < .001$). Conversely and as predicted, there was significantly more OO muscle activity during happy faces than sad faces ($M_{happy} = 1.602$, $SD = 0.140$; $M_{\text{sad}} = 1.358$, $SD = 0.090$; $p = .023$). However, contrary to my predictions, there was no significant difference in ZM activity during happy faces or sad faces ($M_{happy} = 1.215$, $SD = 0.080$; $M_{\text{sad}} = 1.144$, $SD = 0.050$; $p = .240$) I concluded that happy and sad faces elicited patterns of facial mimicry in the predicted direction for CS and OO muscle sites but not for the ZM muscle. Accordingly, ZM was eliminated from all subsequent analyses.

Hypothesis 1: Resting RSA Influences the Degree to Which People Engage in Automatic Facial Mimicry

A multivariate general linear model was used to test whether and to what extent resting RSA predicted the degree of facial mimicry under the Control condition. Facial mimicry was operationalized as EMG activity in emotion-concordant muscle sites: OO and ZM activity during happy faces and CS activity during sad faces. These three sites served as the dependent variables, and the primary predictor was resting RSA (log-transformed); gender, BMI, and physical activity were also included as additional between-participant covariates, as these factors are known in influence RSA (Andrew et al., 2013; Berntson, et al., 1997). Contrary to Hypothesis 1, multivariate tests showed no significant effect of RSA at any mimicry site (Wilks' $\lambda = 0.955$, $F(2, 67) = 1.571$, $p = .215$, $\eta^2 = .045$). Model results are shown in Table D1.

Hypothesis 2: RSA Influences Changes in Automatic Facial Mimicry Under Perceived Safety

Although psychophysiological evidence suggests that the safety-induction was ineffective, a between-participants MANCOVA was nonetheless used to test the hypothesis that under perceived safety, resting RSA influences automatic facial mimicry. To account for individual differences in EMG signal, change in mimicry was calculated for each muscle site (OO and CS) and each face type (happy vs. sad) as raw EMG activity during the Safety condition divided by raw EMG activity during Control condition. Thus, parameter estimates reflect the proportion of mimicry during Safety, relative to Control. Resting RSA (log-transformed) and standard covariates were used as independent variables. Multivariate tests revealed that resting RSA did not have a significant effect on the change in mimicry in the Safety condition (Wilks's $\lambda = .934$, $F(2, 65) = 2.279$, $p = .111$, partial $\eta^2 = .066$).

Hypothesis 3. Resting RSA Influences Changes in Automatic Facial Mimicry Under Perceived Threat

A between-participants MANCOVA was conducted to test whether and to what extent resting RSA influenced facial mimicry following a threat induction. Change in mimicry was calculated as described above, but for EMG signal following the threat induction. Similar to testing Hypothesis 2, the MANCOVA included log-transformed RSA as the primary predictor, controlling for gender, BMI, and physical activity. Multivariate tests revealed a significant effect of resting RSA (Wilks's $\lambda = .828$, $F(2, 67) = 6.977$, $p = .002$, partial $\eta^2 = .172$). Subsequent univariate analyses showed that RSA positively predicted change in mimicry for both happy faces ($B = 0.264$, 95% CI [.013, .515], $p = .039$) and sad faces ($B = 0.328$, 95% CI [.109, .546] $p = .004$). Figure D1 illustrates these findings; for people with low resting RSA, there was essentially no change in mimicry, but for people with mean-to-high levels of RSA, mimicry was greater during the threat condition than the neutral condition, for both happy and sad faces. This finding supports the prediction from Hypothesis 3B that facial mimicry is greater under perceived threat, and that RSA enhances this effect.

APPENDIX E: STUDY 2 ALTERNATIVE METRICS

I observed that in my sample, baseline RSA was positively correlated with vagal withdrawal ($r = .461$, $p < .001$; i.e., greater baseline RSA associated with greater decreases during attention task), but negatively correlated with vagal elevation ($r = -.493$, $p < .001$; i.e., greater baseline RSA associated with less increase during meditation). Although it's possible that higher baseline RSA is associated with these differences due to underlying abilities in vagal regulation, it is also possible that the observed negative association between baseline RSA and vagal elevation reflects a ceiling effect, i.e., constrained vagal elevation difference scores at high baseline values. Moreover, these measures are calculated as averages over several 60-sec periods, and may not capture the full extent of vagal flexibility. Therefore, I was motivated to explore alternative metrics that may better quantify vagal flexibility.

Vagal Flexibility: Slopes and Intercepts

Vagal flexibility is conceptually defined as the ability to shift physiological states in response to changes in the environment (i.e., task-specific demands), so I explored the possibility that this is best captured as the rate of change from the beginning of the task to the end. Vagal withdrawal, quantified as slope, has previously been documented in a study of individuals with pain disorders (Eisenlohr-Moul et al., 2014). To calculate the rate of change in RSA (slope), linear regressions were conducted for each participant, predicting RSA (either during attention task or during meditation) with minute-by-minute time as the only predictor. The unstandardized time coefficients (i.e., slope) for RSA during attention task and RSA during meditation served as each participant's *vagal withdrawal slope (VW-slope)* and *vagal elevation slope (VE-slope),* respectively. *VW-slope* was reverse-scored, such that positive scores indicate greater vagal withdrawal. Together, these two slopes quantify rate-of-change for RSA, so *vagal flexibility slope (VF-slope sum)* was computed as the sum of the two slopes. Distribution of *VW-slope* was normal, and on average, participants showed a pattern of vagal withdrawal (reverse-scored slope: $M = 0.054$, $SD = 0.220$), which was significantly greater than 0, $t(78) = 2.231$, $p = .029$. On the other hand, *VE-slope* was positively skewed ($M = 0.001$, $SD = 0.045$), and a one-sample *t*-test showed that on average, slopes were not different from 0, $t(78) = 0.207$, $p = .837$. However, when *VW-slope* and *VE-slope* are summed together to create *VF-slope*, the distribution of the sum is, on average, greater than 0 ($M = 0.056$, $SD = 0.225$), and a *t*-test revealed that this was significantly different from 0, $t(80) = 2.218$, $p = .029$.

In addition, from these linear regressions that predicted RSA as a function of time, I obtained predicted intercepts during the attention task and meditation task. These intercepts estimated the initial RSA (i.e., at 0 minutes) during the attention task and meditation task, respectively. As would be expected, VW and VE intercepts were highly correlated with baseline RSA ($r = .723$, $p < .001$; $r = .863$, $p < .001$), as well as with each other ($r = .718$, $p < .001$). Furthermore, the VE intercept was significantly higher than baseline RSA ($t(78) = 3.467$, $p = .001$), although the VW intercept did not significantly differ from baseline RSA ($t(78) = 1.184$), $p = .240$). To account for these shifts in initial RSA, *VW-shift* was computed as the difference between baseline RSA and VW intercept, such that positive scores represent greater vagal withdrawal (i.e., baseline was greater than VW intercept); *VE-shift* was computed as the difference between baseline RSA and VE intercept, such that positive scores represent greater vagal elevation (i.e., VE intercept greater than baseline). Then, a *VF-shift* score was computed as the sum of these two variables. These “shift” variables bear resemblance to the vagal withdrawal and vagal elevation variables reported in main analyses, in that both represent changes in raw RSA scores from baseline to task.

For analyses, three models were compared; all included baseline RSA and the three standard covariates of sex, BMI, and physical activity. The first tested only the effect of vagal withdrawal (similar to Set 1 in main text), and included VW-shift and VW-slope. The second tested only the effect of vagal withdrawal (similar to Set 2 in main text), and included VE-shift and VE-slope. The third (similar to Set 3 in main text) tested the combined index vagal flexibility, and included VF-shift and VF-slope.

Results

By and large, no significant effects of any of the slope terms emerged. However, there were several effects found with the intercept terms (VW-shift, VE-shift, or VF-shift). Overall, analyses suggest that the rate of RSA change (i.e., slopes) during the attention task or meditation did not capture variability that predictive of measures of Expressed Compassion. Specific results are summarized below.

Pitch cues (Table E1). Similar to analyses presented in main text, there were no significant effects of vagal functioning on pitch cues; one exception (which does not parallel the main text) is that in Using Set 2 (vagal elevation), there was a significant effect of VE-shift in the predicted direction: greater shifts in vagal elevation were associated with greater reductions in pitch variability when expressing compassion. Despite this one significant parameter estimate, none of the models were significant overall.

Intensity cues (Table E2). The pattern of results is the same as that presented in the main text: An effect of baseline RSA is present, although the effects are in both predicted and opposite directions, depending on the individual parameter. Again, none of the models were overall significant.

Listener-perceived compassion (Table E3). In contrast to the largely null results of pitch and intensity cues reported above, models with Sets 1 – 3 were all overall significant. Similar to the main text analysis, there was a significant effect of VW-shift, opposite of the predicted direction: greater decreases from baseline to initial RSA during attention task (positive VW-shift) predicted lower ratings of perceived compassion. In addition (and in contrast to Set 2 results in the main text), I found a significant effect of VE-shift in the predicted direction: greater shifts from baseline to initial RSA during meditation predicted higher ratings of perceived compassion. No effects for vagal flexibility were found.

Socially-focused language. No effects found for VW or VF models. However, although the overall model is not significant, $R^2 = .114$, $F(6, 67) = 1.434$, $p = .215$, a significant effect of VE-slope emerged opposite to the predicted direction; results suggest that participants who had a greater rate of negative change during meditation used more socially-focused language (B = 2.28, 95% CI [-3.497, -0.015], $p = .048$). These findings diverge from the main text, in which all three models exhibited null results.

Positive emotion words. No effects were found in any of the models.

Anxiety-related words (Table E4). Similar to the main text, there was a significant effect of RSA measures in models using Set 1 and Set 3, each in the opposite direction as predicted. Greater vagal withdrawal from baseline to attention task (VW shift) was associated with a greater likelihood of using anxiety-related words. Furthermore, greater VW-slope (rates of change indicating greater vagal withdrawal during the attention task) also predicted greater likelihood of using anxiety-related words. The same pattern as above was found for vagal flexibility (also opposite of the predicted direction).

Maximum Vagal Flexibility

To address the possibility that the difference between averaged values of RSA from baseline to tasks was not sensitive to the full extent of vagal flexibility, I developed a measure that captured *maximum change in RSA*, independent from baseline. This measure was also developed in an attempt mitigate ceiling effects or potential confounds with individual differences such as neuroticism, which was found to influence baseline RSA. For all analyses, the temporal resolution of RSA was at the minute-by-minute level; thus for these measures, the minimum, maximum, and initial values represent RSA in a given 1-minute bin.

First, *maximum-change vagal withdrawal (VW-max)* was calculated by subtracting the minimum RSA value during the attention task from the initial RSA value (minute 1) of the attention task. Thus, higher scores indicate greater maximum vagal withdrawal, and scores of 0 indicate participants whose initial RSA was also the minimum RSA value. Second, *maximum-change vagal elevation (VE-max)* was calculated by subtracting the initial RSA value during meditation (minute 1) from the maximum RSA value during meditation. Higher scores indicate greater vagal elevation, and scores of 0 indicate participants whose RSA did not increase beyond the initial value. Finally, to compute *maximum vagal flexibility (VF-max sum)*, VW-max and VE-max were summed for a global index of vagal flexibility.

Distributions for vagal withdrawal maximum change and vagal elevation maximum change were each positively skewed. For VW-max, 19 participants were assigned scores of 0 (no evidence of vagal withdrawal), and only 6 participants were assigned scores of 0 for VE-max. The VF-max sum score also exhibited positive skewness (*Median* = 1.809, *IQR* = 1.612). Similar to the primary analyses reported in the main study, three different models were tested: one with VW-max only, one with VE-max only, and one with VF-max sum.

Results

Pitch cues. No effects were found in any of the models.

Intensity cues. No effects were found in any of the models.

Listener-perceived compassion. No effects were found in any of the models.

Socially-focused language. No effect found for the VW max model. In the VE model, which was overall marginally significant, R^2 = .143, F(5,68) = 2.262, p = .058, a significant effect of VE-max emerged opposite of the predicted direction; greater maximum vagal elevation was associated with less usage of socially-focused language (B = -0.125, 95% CI [-0.211, -0.039], p = .005). This pattern was also found for VF-max sum, although the overall model was not significant. These findings diverge from the main text, in which all three models exhibited null results.

Positive emotion words. No effects were found in any of the models.

Anxiety-related words. No effects were found in any of the models.

TABLES

Table 1

Study 1 Descriptive Statistics of Recorded Physiology for Initial, Proximal, and Combined Resting Assessments

Individual Resting Assessments

	Initial Assessment				Proximal Assessment				
	M	*SD*	Median	IQR	*M*	*SD*	Median	IQR	*t*
RSA[a]	—	—	0.087	0.067	—	—	0.082	0.051	3.752 ***
Cardiovascular									
HR	73.280	9.983	—	—	74.075	10.049	—	—	-2.971 **
FPTT	0.285	0.023	—	—	0.286	0.024	—	—	-0.591
FPA[a]	—	—	1.760	0.905	—	—	1.795	1.067	-0.807
Respiration									
RP[a]	—	—	4.118	1.027	—	—	3.778	0.800	3.767 ***
TV[a]	—	—	120.852	20.522	—	—	55.667	7.253	20.745 ***

Combined Resting Period

	Combined Resting Period			
	M	*SD*	Median	IQR
RSA	—	—	0.086	0.060
Cardiovascular				
HR	73.622	9.969	—	—
FPTT	0.2854	0.024	—	—
FPA	—	—	1.791	0.959
Respiration				
RP	—	—	4.056	0.869
TV	—	—	115.789	11.956

Note. RSA = respiratory sinus arrhythmia. HR = heart rate (beats per minute). FPA = finger pulse amplitude. FPTT = finger pulse transit time (s). RP = respiration period (s). TV = tidal volume (mL). IQR = inter-quartile range. a. *t*-tests were conducted on log-transformed variables to meet assumptions of normality. For *t*-tests, $df = 74$ except RP ($df = 73$). $^{**}p < .01$; $^{***}p < .001$.

Table 2

Study 1 Descriptive Statistics of Recorded Physiology During Threat and Safety Conditions

	Safety Condition					Threat Condition				
	M	*SD*	Median	IQR	*t*	*M*	*SD*	Median	IQR	*t*
RSA[a]	—	—	0.071	0.053	-4.754 ***	—	—	0.076	0.048	-3.964 ***
Cardiovascular Measures										
HR	74.131	10.016	—	—	1.364	73.038	9.689	—	—	-1.897[b] †
FPTT	0.287	0.024	—	—	2.421 *	0.287	0.023	—	—	2.516 *
FPA[a]	—	—	1.462	0.936	-5.530 ***	—	—	1.412	0.764	-6.445 ***
Respiration Measures										
RP[a]	—	—	3.613	0.820	-0.974[c]	—	—	3.565	0.674	-2.400 *
TV[a]	—	—	106.706	10.895	-6.805 ***	—	—	105.464	11.919	-7.063 ***

Note. RSA = respiratory sinus arrhythmia. HR = heart rate (beats per minute). FPA = finger pulse amplitude. FPTT = finger pulse transit time (s). RP = respiration period (s). TV = tidal volume (mL). IQR = inter-quartile range. *t* statistics represent differences between condition and resting period, such that positive values indicate resting period > condition. For Threat *t*-tests, $df = 74$. For Safety *t*-tests, $df = 73$ except RSA ($df = 72$). [a]*t*-tests were conducted on log-transformed variables to meet assumptions of normality. [b]HR was significantly lower compared to the proximal assessment, $t(74) = -3.263$, $p = .002$. [c]RP was significantly lower in the the Safety condition than proximal assessment, $t(72) = -3.483$, $p = .001$. *$p < .05$; ***p < .001; †$p < .10$.

Table 3

Study 1 Univariate Estimates of the Relationship Between Resting RSA and Facial Mimicry During the Control Condition

Happy Mimicry (OO)		
$F(4,68) = 1.886$, $p = .123$, Partial $\eta^2 = .100$		
	B	*SE* B
Intercept	-0.310	0.352
Resting RSA	-0.142	0.138
Gender	0.202	0.157
BMI	0.028	0.014 †
Physical Activity	< 0.000	< 0.000
Happy Mimicry (ZM)		
$F(4,68) = 2.040$, $p = .098$, Partial $\eta^2 = .107$		
	B	*SE* B
Intercept	-0.388	0.291
Resting RSA	-0.137	0.114
Gender	0.324	0.130 *
BMI	0.009	0.012
Physical Activity	< 0.000	< 0.000
Sad Mimicry (CS)		
$F(4,68) = 1.042$, $p = .392$, Partial $\eta^2 = .058$		
	B	*SE* B
Intercept	-0.630	0.397
Resting RSA	-0.225	0.156
Gender	0.236	0.178
BMI	0.011	0.016
Physical Activity	< 0.000	< 0.000

Note. OO = orbicularis oculi. ZM = zygomaticus major. CS = corrugator supercilii. Estimates of EMG activity reflect standardized difference scores. RSA = respiratory sinus arrhythmia. For gender, female = 0; male = 1. BMI = body mass index, mean-centered. Physical Activity reflects a weighted index of physical activity per week. *B* = unstandardized coefficients. *SE* = standard error. *$p < .05$; †$p < .10$.

Table 4

Study 1 Repeated-Measures ANCOVA Results, Moderation of Facial Mimicry by Resting RSA

	df	*F*	*p*	Partial η^2
Between-Participants				
Intercept	1	6.764	0.011 *	0.090
Resting RSA	1	3.559	0.063 †	0.050
Gender	1	1.359	0.248	0.020
BMI	1	2.824	0.097 †	0.040
Physical Activity	1	0.023	0.881	0.000
Error	68			
Within-Participants[a]				
Condition	1.000	22.454	0.000 ***	0.248
Condition × Resting RSA	1.000	16.530	0.000 ***	0.196
Condition × Gender	1.000	5.391	0.023 *	0.073
Condition × BMI	1.000	13.771	0.000 ***	0.168
Condition × Physical Activity	1.000	1.860	0.177	0.027
Error	68.000			
Mimicry Type	1.680	2.046	0.142	0.029
Mimicry × Resting RSA	1.680	1.463	0.236	0.021
Mimicry × Gender	1.680	0.020	0.967	0.000
Mimicry × BMI	1.680	0.312	0.694	0.005
Mimicry × Physical Activity	1.680	1.879	0.164	0.027
Error	114.228			
Condition × Mimicry Type	1.719	1.211	0.297	0.017
Condition × Mimicry × Resting RSA	1.719	0.974	0.369	0.014
Condition × Mimicry × Gender	1.719	0.215	0.773	0.003
Condition × Mimicry × BMI	1.719	1.365	0.258	0.020
Condition × Mimicry × Physical Activity	1.719	0.334	0.684	0.005
Error	116.891			

Note. RSA = respiratory sinus arrhythmia. For gender, female = 0; male = 1. BMI = body mass index, mean-centered. Physical Activity reflects a weighted index of physical activity per week. Condition represents Control versus Threat. Mimicry = EMG activity (standardized difference scores) at corrugator supercilii during sad faces, orbicularis oculi during happy faces, and zygomaticus major during happy faces. [a] Within-participant tests violated sphericity assumptions, so degrees of freedom (*df*) reflect Greenhouse-Geisser correction; uncorrected *df* = 2, 136. *$p < .05$; ***$p < .001$; †$p < .10$.

Table 5

Study 2 Correlations Among Primary Independent Variables

	Baseline RSA	**VW**	**VE**	**VF**	**Sex**	**BMI**	**Physical Activity**
RSA Measures							
Baseline RSA	1.00						
VW	0.461***	1.00					
VE	-0.493***	-0.460***	1.00				
VF	0.081	0.679***	0.340**	1.00			
Standard covariates							
Sex	0.221*	0.024	-0.215†	-0.153	1.00		
BMI	0.043	0.092	0.045	0.135	-0.130	1.00	
Physical Activity	0.239*	0.004	-0.044	-0.031	0.161	0.105	1.00

Note. RSA = respiratory sinus arrhythmia (ms^2). VW = vagal withdrawal, ΔRSA between baseline and attention task; higher values indicate greater decreases during attention task. VE = vagal elevation, ΔRSA between baseline and meditation; higher values indicate greater increases during meditation. VF = vagal flexibility, sum of VW and VE. Sex is coded 0 = female, 1 = male. BMI = body mass index. *N* ranged from 78 to 85. **p* < .05, ***p* < .01, ****p* < .001, †*p* < .10

Table 6

Study 2 Correlations Among Dependent Variables of Interest

	Method A						Method B	Method C		
	Change in pitch (Hz)			Change in intensity (dB)						
	Mean	**Variability**	**Range**	**Mean**	**Variability**	**Range**	**Perceived Compassion**	**Social Focus**	**Positive Emotion**	**Anxiety**
Method A, Δ pitch										
Mean	1.00									
Variability	0.079	1.00								
Range	0.028	0.567***	1.00							
Method A, Δ intensity										
Mean	0.178‡	-0.064	-0.051	1.00						
Variability	0.174‡	0.004	0.095	0.279*	1.00					
Range	0.018	-0.035	0.029	0.395***	0.372**	1.00				
Method B										
Perceived Compassion	0.135[b]	-0.071[b]	0.071[b]	0.129[b]	0.021[b]	0.02[b]	1.00			
Method C										
Social Focus	0.207[a]†	-0.052[a]	-0.149[a]	0.032[a]	-0.098[a]	-0.142[b]	0.239[c]*	1.00		
Positive Emotion	0.062[a]	-0.052[a]	0.167[a]‡	0.101[a]	0.105[a]	-0.013[b]	0.126[c]	0.106	1.00	
Anxiety	-0.104[a]	0.043[a]	0.122[a]	0.085[a]	-0.144[a]	0.032[a]	-0.123[c]	-0.247*	-0.098	1.00
RMET	-0.073[c]	0.005[c]	-0.102[c]	-0.134[c]	-0.045[c]	0.126[c]	-0.035[d]	-0.134[b]	0.059[b]	0.072[b]
Recipient suffering	-0.014	0.081	0.096	-0.042	-0.16‡	0.010	0.088[b]	0.295**	-0.136	-0.122
Self-reported compassion	0.021	0.033	0.021	-0.060	-0.176‡	0.036	-0.058[b]	0.267*	-0.17‡	-0.147

Note. Δ pitch = shift in fundamental frequency (F0) from Control message to Expressed Compassion (EC), such that lower values indicate decreased F0 during EC (measured in Hertz, Hz). Δ intensity = shift in intensity (loudness) from Control message to EC, such that lower values indicate decreased intensity during EC (measured in decibels, dB). Mean, variability, and range represent within-message characteristics. Higher perceived compassion values reflect greater perceived compassion. Social Focus = percent of words in EC messages classified as being socially focused. Positive Emotion = percent of words in EC messages classified as positive emotion. Anxiety = percent of words in EC messages classified as being anxiety-related. RMET = Reading the Mind in the Eyes Test score; higher scores reflect greater empathic accuracy. Higher recipient suffering and self-reported compassion values reflect how extreme the participant perceived the message recipient's suffering, and how much compassion they felt, respectively. N = 81, except where [a](N = 80), [b](N=79), [c](N=78). ***p < .001, **p < .01, *p < .05, †p < .10, ‡p < .15.

Table 7

Study 2 Measures of Acoustic Properties of Control and Expressed Compassion Messages

	Control Message		Compassion Message		
Acoustic Property	*M*	*SD*	*M*	*SD*	*t*(80)
Pitch, F0 (Hz)					
Mean	159.35	38.02	154.68	39.24	2.83**
Variability	45.71	16.80	45.59	20.87	0.07
Range	351.78	94.05	315.64	109.71	2.70**
Intensity (dB)					
Mean	67.56	4.08	65.63	3.90	[a]10.18***
Variability	4.79	0.74	4.48	0.78	5.59***
Range	29.90	4.25	28.50	4.45	[a]3.71***

Note. Acoustic properties were calculated within-message across all voiced segments. [a]*t*-test was performed on log-transformed values to meet assumptions of normality. ** $p < .01$; *** $p \leq .001$.

Table 8

Study 2 Models Predicting Intensity Cues During Expressed Compassion Messages

Δ Intensity Mean									
	Set 1: Vagal Withdrawal $R^2 = .124$, $F(5, 69) = 1.962$, $p = .095$			**Set 2: Vagal Elevation** $R^2 = .098$, $F(5, 69) = 1.495$, $p = .203$			**Set 3: Vagal Flexibility Sum** $R^2 = .118$, $F(5, 69) = 1.847$, $p = .115$		
	B	*SE* B	β	B	*SE* B	β	B	*SE* B	β
Constant	0.009	0.019		-0.001	0.020		-0.003	0.017	
Sex	-0.002	0.007	-0.039	-0.003	0.007	-0.052	-0.002	0.007	-0.031
BMI	-0.001	0.001	-0.120	-0.001	0.001	-0.103	-0.001	0.001	-0.125
Physical Activity	< 0.000	0.000	-0.140	< 0.000	0.000	-0.159	< 0.000	0.000	-0.153
Baseline RSA	-0.006	0.003	**-0.273** *	-0.004	0.003	-0.192	-0.004	0.003	-0.197
Vagal Withdrawal	0.006	0.004	0.188	—	—	—	—	—	—
Vagal Elevation	—	—	—	-0.001	0.006	-0.024	—	—	—
Vagal Flexibility	—	—	—	—	—	—	0.005	0.004	0.148

Δ Intensity Variability									
	Set 1: Vagal Withdrawal $R^2 = .073$, $F(5, 69) = 1.084$, $p = .377$			**Set 2: Vagal Elevation** $R^2 = .093$, $F(5, 69) = 1.417$, $p = .229$			**Set 3: Vagal Flexibility Sum** $R^2 = .084$, $F(5, 69) = 1.273$, $p = .286$		
	B	*SE* B	β	B	*SE* B	β	B	*SE* B	β
Constant	-0.908	0.353	*	-1.167	0.374	**	-0.916	0.315	**
Sex	0.14	0.125	0.137	0.154	0.124	0.151	0.154	0.125	0.151
BMI	0.001	0.012	0.009	0	0.012	-0.001	-0.001	0.012	-0.006
Physical Activity	< 0.000	0.000	-0.107	< 0.000	0.000	-0.119	< 0.000	0.000	-0.101
Baseline RSA	0.086	0.057	0.210	0.122	0.057	**0.298** **	0.082	0.05	0.201
Vagal Withdrawal	0.004	0.082	0.006	—	—	—	—	—	—
Vagal Elevation	—	—	—	0.134	0.108	0.167	—	—	—
Vagal Flexibility	—	—	—	—	—	—	0.073	0.078	0.111

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	Δ Intensity Range								
	Set 1: Vagal Withdrawal			**Set 2: Vagal Elevation**			**Set 3: Vagal Flexibility Sum**		
	R^2 = .142, F(5, 69) = 2.275, p = .057			R^2 = .092, F(5, 69) = 1.394, p = .237			R^2 = .137, F(5, 69) = 2.182, p = .066		
	B	*SE* B	β	B	*SE* B	β	B	*SE* B	β
Constant	-0.025	0.087		-0.099	0.096		-0.101	0.079	
Sex	-0.016	0.031	-0.061	-0.02	0.032	-0.075	-0.012	0.031	-0.047
BMI	-0.008	0.003	**-0.316** **	-0.008	0.003	**-0.295** *	-0.008	0.003	**-0.326** **
Physical Activity	< 0.000	0.000	0.133	< 0.000	0.000	0.106	< 0.000	0.000	0.117
Baseline RSA	-0.004	0.014	-0.04	0.009	0.015	0.084	0.007	0.012	0.062
Vagal Withdrawal	0.04	0.02	**0.255** *	—	—	—	—	—	—
Vagal Elevation	—	—	—	-0.001	0.028	-0.005	—	—	—
Vagal Flexibility	—	—	—	—	—	—	0.037	0.02	0.217 †

Note. Δ Intensity Mean = log-transformed difference between mean intensity (decibels) during control and expressed compassion (EC) messages. Δ Intensity Variability = difference between intensity variability (decibels) during control and EC messages. Δ Intensity Range = log-transformed difference between intensity range (decibels) during control and EC messages. For all change (Δ) scores, positive values indicate an increase in acoustic property during EC message. RSA = respiratory sinus arrhythmia. Vagal Withdrawal = difference between RSA during baseline and attention task; positive values indicate greater decreases. Vagal Elevation = difference between RSA during baseline and meditation; positive values indicate greater increases. Vagal Flexibility = sum of Vagal Withdrawal and Vagal Elevation scores. For Sex, 0 = female; 1 = male. BMI = body mass index, mean-centered. Physical Activity reflects a weighted index score of weekly physical activity, mean centered. B = unstandardized coefficient. *SE* = standard error. β = standardized coefficient. ***p* < .01; **p* < .05; †*p* < .10.

Table 9

Study 2 Models Predicting Listener-Perceived Compassion of Expressed Compassion Messages

	Set 1: Vagal Withdrawal R^2 = .292, $F(6, 66) = 4.540$, $p = .001$**			Set 2: Vagal Elevation R^2 = .244, $F(6, 66) = 3.548$, $p = .004$**			Set 3: Vagal Flexibility R^2 = .226, $F(6, 66) = 3.209$, $p = .008$**		
	B	*SE* B	β	B	*SE* B	β	B	*SE* B	β
Constant	2.673	0.645	***	2.836	0.675	***	3.239	0.636	***
PC, control	0.200	0.122	0.176	0.173	0.126	0.152	0.180	0.128	0.158
Sex	-0.459	0.144	**-0.357****	-0.416	0.149	**-0.323****	-0.462	0.151	**-0.359****
BMI	-0.029	0.013	**-0.226***	-0.034	0.014	**-0.267***	-0.029	0.014	**-0.232***
Physical Activity	< 0.000	0.000	-0.079	< 0.000	0.000	-0.062	< 0.000	0.000	-0.052
Baseline RSA	0.096	0.063	0.187	0.069	0.066	0.135	0.019	0.059	0.037
Vagal Withdrawal	-0.259	0.092	**-0.336****	—	—	—	—	—	—
Vagal Elevation	—	—	—	0.227	0.125	0.228†	—	—	—
Vagal Flexibility	—	—	—	—	—	—	-0.119	0.092	-0.145

Note. PC, control = listener-perceived compassion of Control messages. RSA = respiratory sinus arrhythmia. Vagal Withdrawal = difference between RSA during baseline and attention task; positive values indicate greater decreases. Vagal Elevation = difference between RSA during baseline and meditation; positive values indicate greater increases. Vagal Flexibility = sum of Vagal Withdrawal and Vagal Elevation scores. For Sex, 0 = female; 1 = male. BMI = body mass index, mean-centered. Physical Activity reflects a weighted index score of weekly physical activity, mean centered. B = unstandardized coefficient. *SE* = standard error. β = standardized coefficient. ***$p < .001$; **$p < .01$; *$p < .05$; $^{\dagger}p < .10$.

Table 10

Study 2 Descriptive Statistics of Linguistic Content of Compassion Messages

LIWC Category	***Median***	***25th Percentile***	***75th Percentile***
Word count	117.00	81.00	164.00
Dictionary	97.44	96.59	98.73
Personal pronouns (overall)	18.70	15.63	20.99
1st person singular	6.28	4.16	8.64
1st person plural	0.00	0.00	1.38
2nd person	10.47	8.34	11.59
Affective processes (overall)	6.17	4.67	8.03
Positive emotion	4.65	3.12	6.34
Negative emotion	1.56	0.87	2.47
Anxiety	0.00	0.00	0.40
Anger	0.00	0.00	0.00
Sad	0.00	0.00	1.00
Social processes (overall)	16.95	13.74	20.79
Cognitive processes (overall)	16.81	13.69	19.37
Affiliation	2.52	1.40	3.78
Past focus	1.93	0.80	3.48
Present focus	17.28	15.04	19.52
Future focus	1.75	0.80	3.64
Non-fluencies	3.33	1.70	5.81
Fillers	0.00	0.00	1.23

Note. Values represent percentage of total words (with exception of Word Count). Non-parametric statistics calculated due to skewness in most variables. Categories in bold were chosen for primary analyses. Total analysis sample N = 81.

Table 11

Study 2 Models Predicting Probability of Anxiety Words in Expressed Compassion Messages

	Set 1: Vagal Withdrawal			Set 2: Vagal Elevation			Set 3: Vagal Flexibility		
	B	*SE* B	*OR*	B	*SE* B	*OR*	B	*SE* B	*OR*
Constant	2.202	2.018	9.044	-0.390	1.889	0.677	-1.160	1.710	0.313
Sex	-0.813	0.729	0.444	-0.818	0.669	0.441	-0.608	0.694	0.544
BMI	-0.092	0.069	0.912	-0.058	0.062	0.944	-0.095	0.069	0.910
Physical Activity	0.000	0.000	1.000	0.000	0.000	1.000	0.000	0.000	1.000
Baseline RSA	-0.581	0.337	0.559†	-0.076	0.286	0.927	-0.068	0.269	0.934
Vagal Withdrawal	1.860	0.617	**6.422****	—	—	—	—	—	—
Vagal Elevation	—	—	—	-0.273	0.560	0.761	—	—	—
Vagal Flexibility	—	—	—	—	—	—	1.275	0.504	**3.580***

Note. RSA = respiratory sinus arrhythmia. Vagal Withdrawal = difference between RSA during baseline and attention task; positive values indicate greater decreases. Vagal Elevation = difference between RSA during baseline and meditation; positive values indicate greater increases. Vagal Flexibility = sum of Vagal Withdrawal and Vagal Elevation scores. For Sex, 0 = female; 1 = male. BMI = body mass index, mean-centered. Physical Activity reflects a weighted index score of weekly physical activity, mean centered. B = unstandardized coefficient. *SE* = standard error. *OR* = odds ratio. **$p < .01$; *$p < .05$; $^{\dagger}p < .10$.

Table B1

Study 1 Duration of Dynamic Facial Expressions

Image	**Duration (ms)**
Neutral expression (start)	333
Neutral morph to Emotion	533
Emotion expression	1667
Emotion morph to Neutral	567
Neutral expression (end)	500
TOTAL	**3600**

Table C1

Study 1 Descriptive Statistics of Sound Stimuli

Dimension	**Safety** *M (SD)*	**Threat** *M (SD)*
Arousal	4.80 (0.96)	7.33 (0.52)
Pleasure	6.93 (0.54)	2.23 (0.49)
Dominance	6.00 (0.32)	2.83 (0.38)

Table D1

Study 1 Univariate Estimates of Resting RSA's Influence on Facial Mimicry During the Control Condition

Happy Mimicry (OO)		
$F(4,68) = 0.578$, $p = .680$, Partial $\eta^2 = .033$		
	B	*SE* B
Intercept	1.281	0.726 †
Resting RSA	-0.126	0.284
Gender	0.089	0.325
BMI	0.035	0.029 †
Physical Activity	< 0.000	< 0.000
Sad Mimicry (CS)		
$F(4,68) = 1.547$, $p = .199$, Partial $\eta^2 = .083$		
	B	*SE* B
Intercept	1.945	0.338 ***
Resting RSA	0.211	0.132
Gender	-0.189	0.151
BMI	0.010	0.014
Physical Activity	< 0.000	< 0.000

Note. OO = orbicularis oculi. CS = corrugator supercilii. Estimates of EMG activity reflect standardized difference scores. RSA = respiratory sinus arrhythmia. For gender, female = 0; male = 1. BMI = body mass index, mean-centered. Physical Activity reflects a weighted index of physical activity per week. *B* = unstandardized coefficients. *SE* = standard error. ***$p < .001$; †$p < .10$.

Table E1

Study 2 Models of RSA Slopes and Intercepts Predicting Pitch Cues During Expressed Compassion

	Δ Pitch Mean								
	Set 1: Vagal Withdrawal (VW) R^2 = .044, F(6, 68) = 0.527, p = .786			**Set 2: Vagal Elevation (VE)** R^2 = .063, F(6, 68) = 0.764, p = .601			**Set 3: Vagal Flexibility (VF)** R^2 = .048, F(6, 68) = 0.566, p = .756		
	B	*SE* B	β	B	*SE* B	β	B	*SE* B	β
Constant	-7.086	11.424		-14.412	11.952		-3.842	10.256	
Sex	3.349	4.076	0.104	3.680	4.024	0.114	3.827	4.084	0.119
BMI	-0.015	0.392	-0.005	-0.106	0.389	-0.033	-0.069	0.393	-0.022
Physical Activity	0.000	0.000	-0.014	0.000	0.000	-0.019	0.000	0.000	-0.003
Baseline RSA	0.233	1.835	0.018	1.204	1.807	0.093	-0.405	1.624	-0.031
VW shift	-1.928	2.686	-0.109	—	—	—	—	—	—
VW slope	8.646	9.469	0.126	—	—	—	—	—	—
VE shift	—	—	—	5.584	3.598	0.211	—	—	—
VE slope	—	—	—	67.077	41.301	0.201	—	—	—
VF shift	—	—	—	—	—	—	0.547	2.475	0.030
VF slope	—	—	—	—	—	—	14.367	8.932	0.215

	Δ Pitch Variability								
	Set 1: Vagal Withdrawal R^2 = .066, F(6, 68) = 0.804, p = .570			**Set 2: Vagal Elevation** R^2 = .115, F(6, 68) = 1.467, p = .203			**Set 3: Vagal Flexibility** R^2 = .055, F(6, 68) = 0.662, p = .681		
	B	*SE* B	β	B	*SE* B	β	B	*SE* B	β
Constant	0.794	11.959		10.007	12.305		-4.782	10.818	
Sex	1.104	4.266	0.032	-0.072	4.143	-0.002	0.632	4.308	0.019
BMI	-0.485	0.410	-0.143	-0.355	0.401	-0.105	-0.421	0.415	-0.124
Physical Activity	0.001	0.000	0.193	0.001	0.000	0.191	0.001	0.000	0.172
Baseline RSA	-0.248	1.921	-0.018	-1.253	1.860	-0.092	0.822	1.713	0.060
VW shift	2.804	2.812	0.149	—	—	—	—	—	—
VW slope	8.029	9.913	0.110	—	—	—	—	—	—
VE shift	—	—	—	-8.003	3.704	**-0.285** *	—	—	—
VE slope	—	—	—	-42.079	42.522	-0.119	—	—	—
VF shift	—	—	—	—	—	—	-1.294	2.611	-0.066
VF slope	—	—	—	—	—	—	0.164	9.421	0.002

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	Δ Pitch Range								
	Set 1: Vagal Withdrawal R^2 = .012, F(6, 68) = 0.136, p = .991			**Set 2: Vagal Elevation** R^2 = .052, F(6, 68) = 0.717, p = .717			**Set 3: Vagal Flexibility** R^2 = .015, F(6, 68) = 0.173, p = .983		
	B	*SE* B	β	B	*SE* B	β	B	*SE* B	β
Constant	-88.125	92.166		-71.147	95.412		-98.253	82.749	
Sex	6.588	32.882	0.026	9.874	32.125	0.039	6.172	32.954	0.024
BMI	0.959	3.162	0.038	0.696	3.106	0.027	1.140	3.173	0.045
Physical Activity	-0.001	0.003	-0.023	-0.001	0.003	-0.031	-0.001	0.003	-0.031
Baseline RSA	8.327	14.805	0.081	6.264	14.422	0.061	10.502	13.106	0.102
VW shift	3.857	21.669	0.027	—	—	—	—	—	—
VW slope	-1.346	76.397	-0.002	—	—	—	—	—	—
VE shift	—	—	—	-23.417	28.719	-0.111	—	—	—
VE slope	—	—	—	412.141	329.708	0.155	—	—	—
VF shift	—	—	—	—	—	—	-9.666	19.973	-0.066
VF slope	—	—	—	—	—	—	-4.170	72.067	-0.008

Note. Δ Pitch Mean = difference between mean pitch (Hertz) during control and Expressed Compassion (EC) messages. Δ Pitch Variability = difference between pitch variability (Hertz) during control and EC messages. Δ Pitch Range = difference between pitch range (Hertz) during control and EC messages. For all change (Δ) scores, positive values indicate an increase in acoustic property during EC message. RSA = respiratory sinus arrhythmia. Vagal Withdrawal = difference between RSA during baseline and attention task, such that positive values reflect greater decrease. Vagal Elevation = difference between RSA during baseline and meditation; positive values indicate greater increases. *Shift* reflects difference between baseline RSA and initial RSA during attention task (VW), meditation (VE), of sum of VW and VE (VF); greater values indicate greater shift in predicted direction. *Slope* reflects rate of change (per minute) in RSA during either the attention task (VW slope) or meditation (VE slope); positive slope indicates change in predicted direction; VF slope is sum of VW slope and VE slope. For *Sex*, 0 = female; 1 = male. *BMI* = body mass index, mean-centered. *Physical Activity* reflects a weighted index score of weekly physical activity, mean centered. B = unstandardized coefficient. *SE* = standard error. β = standardized coefficient. *p < .05.

Table E2

Study 2 Models of RSA Slopes and Intercepts Predicting Intensity Cues During Expressed Compassion

Δ Intensity Mean

	Set 1: Vagal Withdrawal (VW) R^2 = .132, F(6, 68) = 1.718, p = .130			**Set 2: Vagal Elevation (VE)** R^2 = .100, F(6, 68) = 1.256, p = .290			**Set 3: Vagal Flexibility (VF)** R^2 = .127, F(6, 68) = 1.646, p = .148		
	B	*SE* B	β	B	*SE* B	β	B	*SE* B	β
Constant	0.011	0.019		-0.004	0.020		-0.002	0.017	
Sex	-0.002	0.007	-0.036	-0.002	0.007	-0.044	-0.002	0.007	-0.031
BMI	-0.001	0.001	-0.123	-0.001	0.001	-0.110	-0.001	0.001	-0.128
Physical Activity	0.000	0.000	-0.137	0.000	0.000	-0.164	0.000	0.000	-0.145
Baseline RSA	-0.006	0.003	**-0.287** *	-0.004	0.003	-0.171	-0.005	0.003	-0.208
VW shift	0.007	0.004	0.235	—	—	—	—	—	—
VW slope	0.015	0.015	0.124	—	—	—	—	—	—
VE shift	—	—	—	0.000	0.006	0.007	—	—	—
VE slope	—	—	—	0.030	0.069	0.052	—	—	—
VF shift	—	—	—	—	—	—	0.006	0.004	0.192
VF slope	—	—	—	—	—	—	0.013	0.015	0.111

Δ Intensity Variability

	Set 1: Vagal Withdrawal R^2 = .077, F(6, 68) = 0.940, p = .472			**Set 2: Vagal Elevation** R^2 = .092, F(6, 68) = 1.144, p = .347			**Set 3: Vagal Flexibility** R^2 = .085, F(6, 68) = 1.058, p = .396		
	B	*SE* B	β	B	*SE* B	β	B	*SE* B	β
Constant	-0.862	0.356	*	-1.130	0.373	**	-0.896	0.318	**
Sex	0.135	0.127	0.133	0.155	0.126	0.152	0.144	0.127	0.142
BMI	0.001	0.012	0.009	-0.001	0.012	-0.007	0.000	0.012	-0.001
Physical Activity	0.000	0.000	-0.102	0.000	0.000	-0.116	0.000	0.000	-0.097
Baseline RSA	0.079	0.057	0.193	0.116	0.056	**0.284** *	0.080	0.050	0.196
VW shift	0.027	0.084	0.047	—	—	—	—	—	—
VW slope	-0.062	0.295	-0.028	—	—	—	—	—	—

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VE shift	—	—	—	0.109	0.112	0.130	—	—	—
VE slope	—	—	—	1.160	1.288	0.110	—	—	—
VF shift	—	—	—	—	—	—	0.071	0.077	0.121
VF slope	—	—	—	—	—	—	0.043	0.277	0.020

Δ Intensity Range

	Set 1: Vagal Withdrawal R^2 = .149, *F*(6, 68) = 1.990, *p* = .079			**Set 2: Vagal Elevation** R^2 = .106, *F*(6, 68) = 1.342, *p* = .251			**Set 3: Vagal Flexibility** R^2 = .133, *F*(6, 68) = 1.739, *p* = .125		
	B	*SE* B	β	B	*SE* B	β	B	*SE* B	β
Constant	-0.021	0.088		-0.101	0.095		-0.097	0.079	
Sex	-0.014	0.031	-0.052	-0.017	0.032	-0.064	-0.012	0.032	-0.046
BMI	-0.008	0.003	-0.321	-0.008	0.003	**-0.306** *	-0.008	0.003	**-0.326** **
Physical Activity	0.000	0.000	0.135	0.000	0.000	0.100	0.000	0.000	0.122
Baseline RSA	-0.005	0.014	-0.050	0.009	0.014	0.087	0.006	0.013	0.055
VW shift	0.043	0.021	**0.297** *	—	—	—	—	—	—
VW slope	0.108	0.073	0.193	—	—	—	—	—	—
VE shift	—	—	—	-0.006	0.029	-0.028	—	—	—
VE slope	—	—	—	0.305	0.328	0.112	—	—	—
VF shift	—	—	—	—	—	—	0.032	0.019	0.211
VF slope	—	—	—	—	—	—	0.094	0.069	0.174

Note. Δ Intensity Mean = log-transformed difference between mean intensity (decibels) during control and Expressed Compassion (EC) messages. Δ Intensity Variability = difference between intensity variability (decibels) during control and EC messages. Δ Intensity Range = log-transformed difference between pitch range (Hertz) during control and EC messages. For all change (Δ) scores, positive values indicate an increase in acoustic property during EC message. RSA = respiratory sinus arrhythmia. Vagal Withdrawal = difference between RSA during baseline and attention task, such that positive values reflect greater decrease. Vagal Elevation = difference between RSA during baseline and meditation; positive values indicate greater increases. *Shift* reflects difference between baseline RSA and initial RSA during attention task (VW), meditation (VE), of sum of VW and VE (VF); greater values indicate greater shift in predicted direction. *Slope* reflects rate of change (per minute) in RSA during either the attention task (VW slope) or meditation (VE slope); positive slope indicates change in predicted direction; VF slope is sum of VW slope and VE slope. For *Sex*, 0 = female; 1 = male. *BMI* = body mass index, mean-centered. *Physical Activity* reflects a weighted index score of weekly physical activity, mean centered. B = unstandardized coefficient. *SE* = standard error. β = standardized coefficient. **p* < .05; ***p* < .01.

Table E3

Study 2 Models of RSA Slopes and Intercepts Predicting Perceived Compassion of Expressed Compassion Messages

	Set 1: Vagal Withdrawal (VW) R^2 = .283, $F(7, 65) = 3.658$, p = .002**			**Set 2: Vagal Elevation (VE)** R^2 = .287, $F(7, 65) = 3.734$, p = .002**			**Set 3: Vagal Flexibility (VF)** R^2 = .216, $F(7, 65) = 2.552$, p = .022*		
	B	*SE* B	β	B	*SE* B	β	B	*SE* B	β
Constant	2.740	0.661		2.667	0.655	***	3.285	0.651	***
PC, Control	0.187	0.126	0.165	0.173	0.123	0.152	0.160	0.131	0.141
Sex	-0.456	0.146	**-0.355** **	-0.406	0.146	**-0.316** **	-0.443	0.153	**-0.344** **
BMI	-0.029	0.014	**-0.232** *	-0.036	0.014	**-0.281** *	-0.032	0.014	**-0.249** *
Physical Activity	0.000	0.000	-0.080	0.000	0.000	-0.060	0.000	0.000	-0.054
Baseline RSA	0.091	0.065	0.178	0.091	0.064	0.178	0.017	0.060	0.034
VW shift	-0.244	0.094	**-0.346** *	—	—	—	—	—	—
VW slope	-0.284	0.342	-0.102	—	—	—	—	—	—
VE shift	—	—	—	0.329	0.126	**0.314** *	—	—	—
VE slope	—	—	—	1.990	1.452	0.151	—	—	—
VF shift	—	—	—	—	—	—	0.088	0.337	0.033
VF slope	—	—	—	—	—	—	-0.060	0.091	-0.081

Note. PC, control = listener-perceived compassion of Control messages. RSA = respiratory sinus arrhythmia. Vagal Withdrawal = difference between RSA during baseline and attention task, such that positive values reflect greater decrease. Vagal Elevation = difference between RSA during baseline and meditation; positive values indicate greater increases. *Shift* reflects difference between baseline RSA and initial RSA during attention task (VW), meditation (VE), of sum of VW and VE (VF); greater values indicate greater shift in predicted direction. *Slope* reflects rate of change (per minute) in RSA during either the attention task (VW slope) or meditation (VE slope); positive slope indicates change in predicted direction; VF slope is sum of VW slope and VE slope. For Sex, 0 = female; 1 = male. BMI = body mass index, mean-centered. Physical Activity reflects a weighted index score of weekly physical activity, mean centered. B = unstandardized coefficient. *SE* = standard error. β = standardized coefficient. ***$p < .001$; **$p < .01$; *$p < .05$.

Table E4

Study 2 Models of RSA Slopes and Intercepts Predicting Probability of Anxiety Words in Expressed Compassion Messages

	Set 1: Vagal Withdrawal (VW)			**Set 2: Vagal Elevation (VE)**			**Set 3: Vagal Flexibility (VF)**		
	B	*SE* B	*OR*	B	*SE* B	*OR*	B	*SE* B	*OR*
Constant	2.121	2.051	8.341	-0.248	1.863	0.781	-0.931	1.728	0.394
Sex	-0.599	0.739	0.549	-0.824	0.672	0.438	-0.512	0.694	0.599
BMI	-0.099	0.071	0.906	-0.056	0.063	0.945	-0.091	0.069	0.913
Physical Activity	0.000	0.000	1.000	0.000	0.000	1.000	0.000	0.000	1.000
Baseline RSA	-0.603	0.343	0.547†	-0.094	0.283	0.910	-0.113	0.274	0.894
VW shift	1.927	0.648	**6.872****	—	—	—	—	—	—
VW slope	5.426	1.957	**227.267****	—	—	—	—	—	—
VE shift	—	—	—	-0.366	0.567	0.693	—	—	—
VE slope	—	—	—	-1.881	6.831	0.152	—	—	—
VF shift	—	—	—	—	—	—	3.320	1.492	**27.661***
VF slope	—	—	—	—	—	—	1.084	0.471	**2.955***

Note. RSA = respiratory sinus arrhythmia. Vagal Withdrawal = difference between RSA during baseline and attention task, such that positive values reflect greater decrease. Vagal Elevation = difference between RSA during baseline and meditation; positive values indicate greater increases. *Shift* reflects difference between baseline RSA and initial RSA during attention task (VW), meditation (VE), of sum of VW and VE (VF); greater values indicate greater shift in predicted direction. *Slope* reflects rate of change (per minute) in RSA during either the attention task (VW slope) or meditation (VE slope); positive slope indicates change in predicted direction; VF slope is sum of VW slope and VE slope. For Sex, 0 = female; 1 = male. BMI = body mass index, mean-centered. Physical Activity reflects a weighted index score of weekly physical activity, mean centered. B = unstandardized coefficient. *SE* = standard error. *OR* = odds ratio. ***p* < .01; **p* < .05; $^{\dagger}p < .10$.

FIGURES

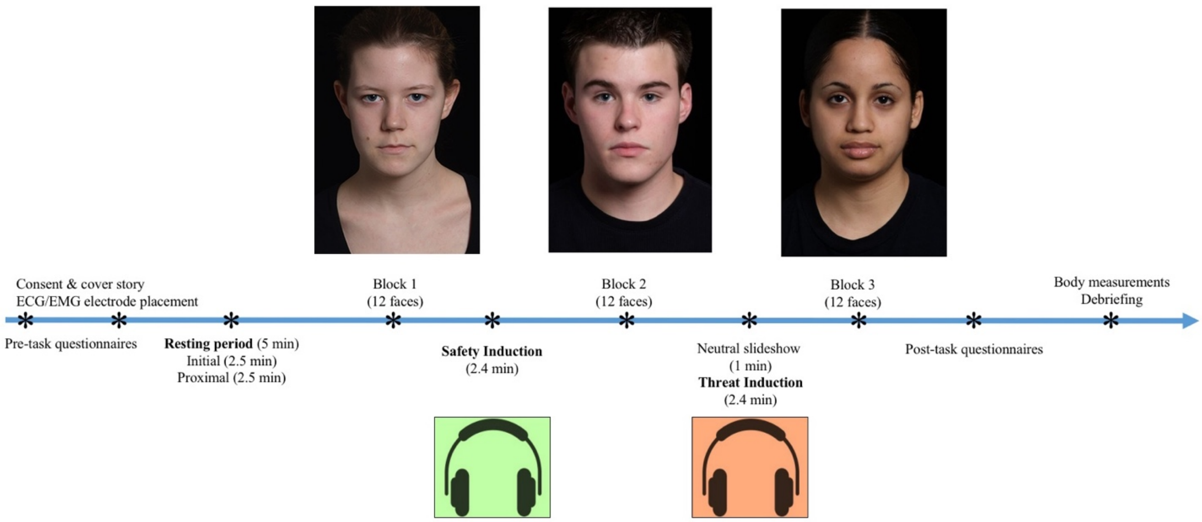

Figure 1. Schematic of Study 1 study design. The order of threat induction and safety induction was counterbalanced. The order of face stimuli for each block was pseudo-randomized among participants.

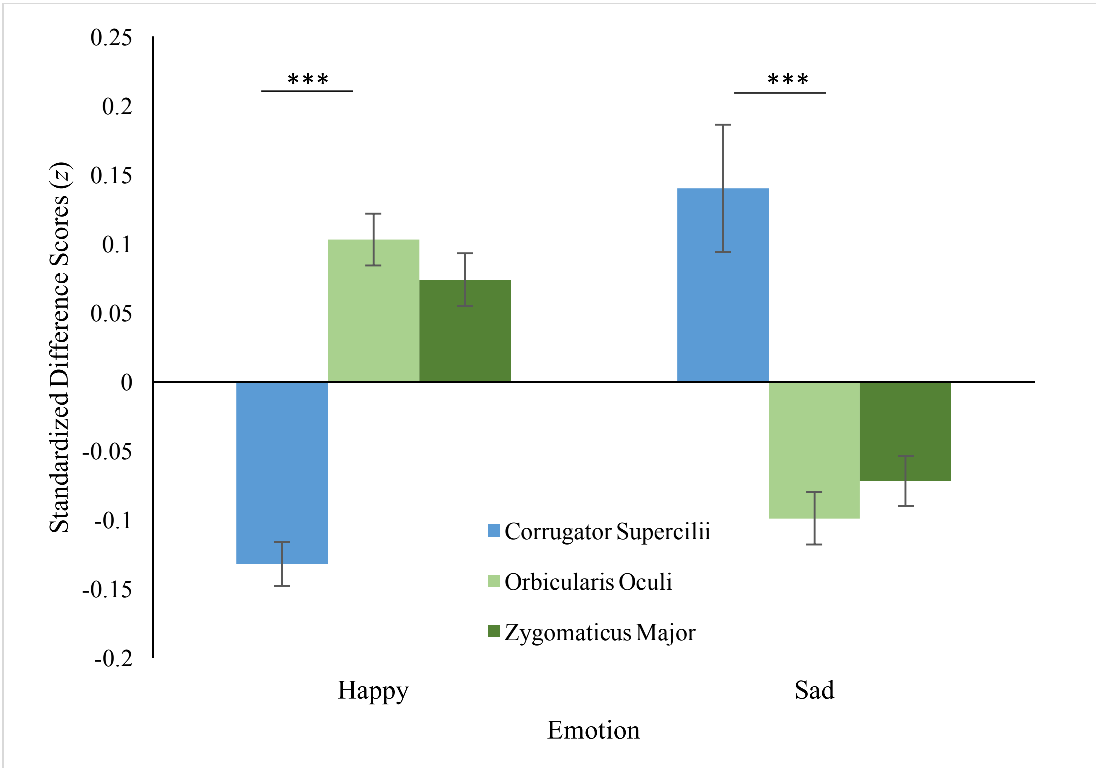

Figure 2. Study 1, facial EMG activity during emotional face stimuli. ***$p < .001$.

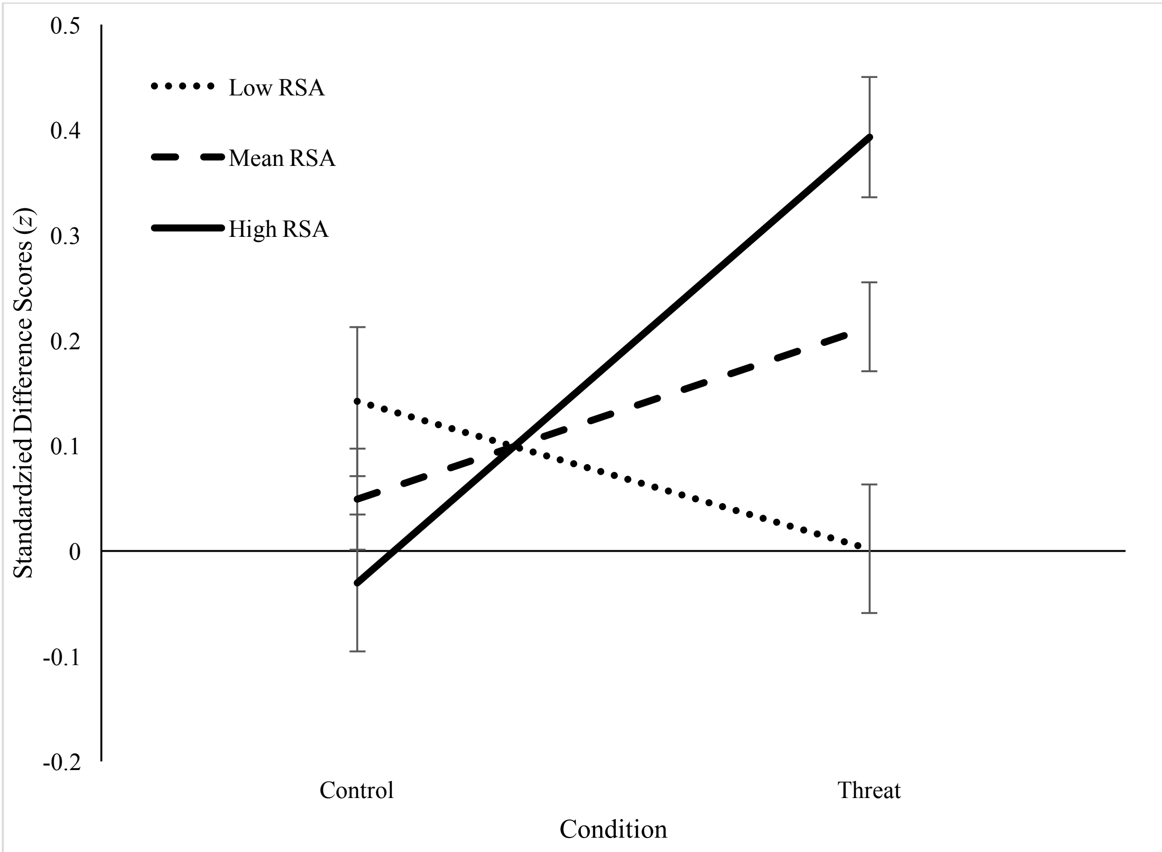

Figure 3. Study 1, change in facial mimicry during threat is moderated by resting RSA. RSA = respiratory sinus arrhythmia. Values represent estimated marginal means across all mimicry sites, for low (-1 SD), mean, and high (+1 SD) log-transformed RSA.

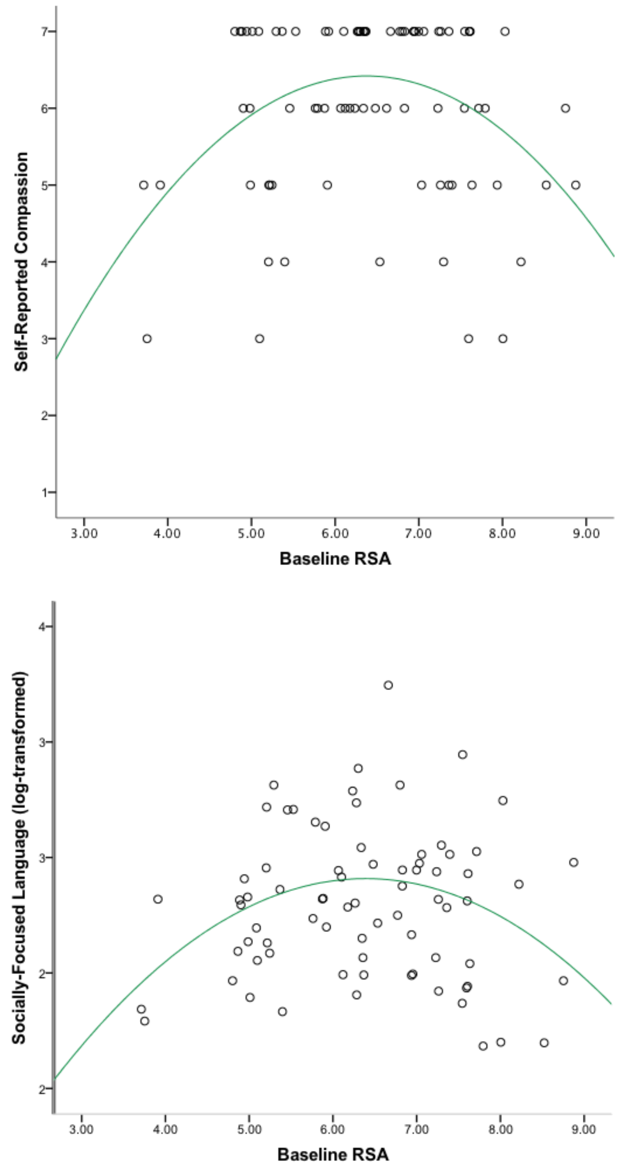

Figure 4. Study 2 baseline RSA's quadratic relationship with self-reported compassion and socially-focused language. RSA = respiratory sinus arrhythmia. Green lines represent the predicted values from parameter estimates of the quadratic equation. Socially-focused language is the percent of socially-focused words used in expressed compassion messages (log-transformed).

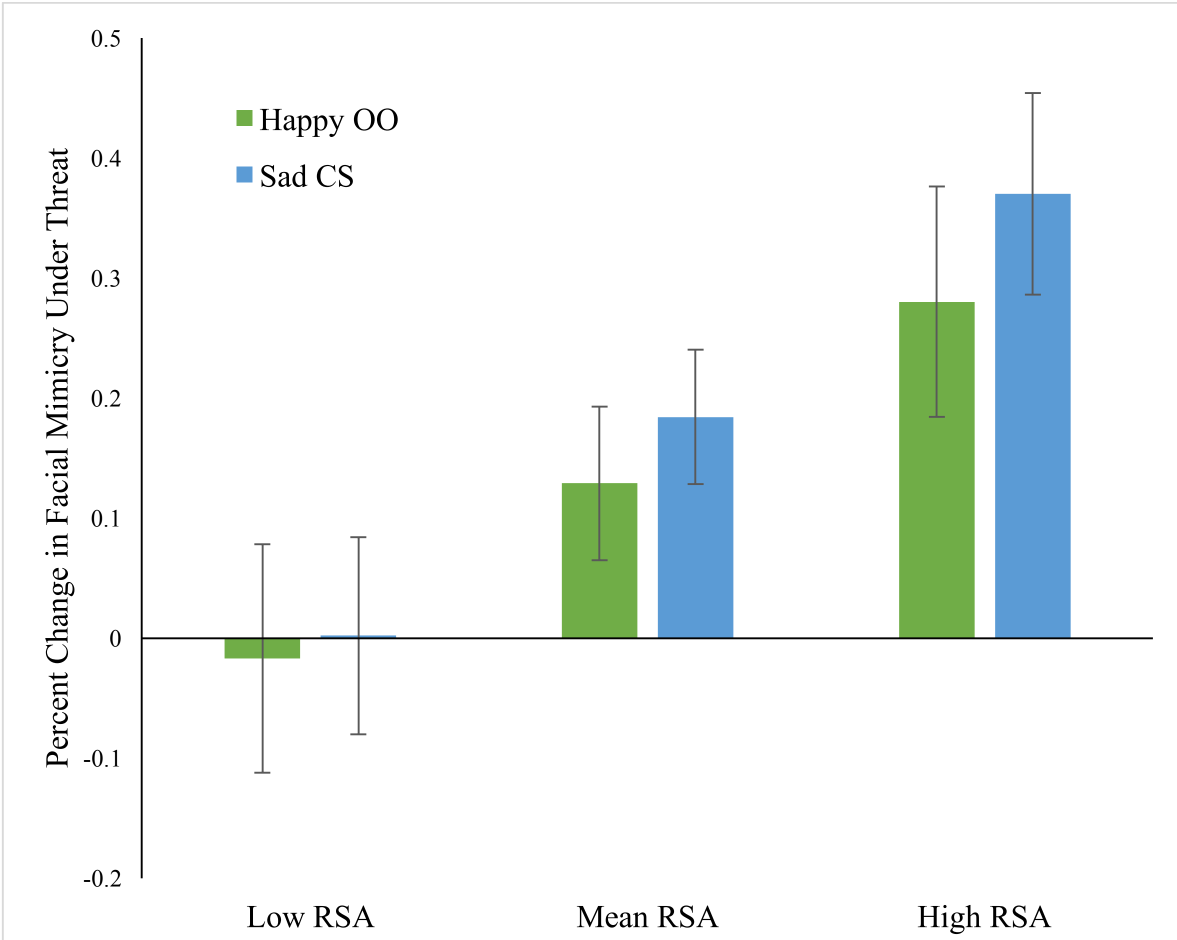

Figure D1. Resting RSA Predicts Change in Mimicry Under Perceived Threat. Happy OO = EMG activity in the orbicularis oculi during happy faces. Sad CS = EMG activity in the corrugator supercilii during sad faces. RSA = respiratory sinus arrhythmia. Low = 1 SD below mean. High = 1 SD above mean.

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