Emotion

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BRIEF REPORT

Too Much of a Good Thing? Cardiac Vagal Tone's Nonlinear Relationship With Well-Being

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Parasympathetic regulation of heart rate through the vagus nerve—often measured as resting respiratory sinus arrhythmia or cardiac vagal tone (CVT)—is a key biological correlate of psychological well-being. However, recent theorizing has suggested that many biological and psychological processes can become maladaptive when they reach extreme levels. This raises the possibility that CVT might not have an unmitigated positive relationship with well-being. In line with this reasoning, across 231 adult participants (M_{age} = 40.02 years; 52% female), we found that CVT was quadratically related to multiple measures of well-being, including life satisfaction and depressive symptoms. Individuals with moderate CVT had higher well-being than those with low or high CVT. These results provide the first direct evidence of a nonlinear relationship between CVT and well-being, adding to a growing body of research that has suggested some biological processes may cease being adaptive when they reach extreme levels.

Keywords: cardiac vagal tone, parasympathetic, well-being, happiness, depression

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An ongoing question in psychological science generally and affective science specifically is what biological processes are associated with and support human well-being (Kogan et al., 2011). The vagus nerve—the parasympathetic nervous system's primary regulator of heart rate—in particular has emerged as a key biological correlate of psychological processes critical to well-being (Beauchaine, 2001; Porges, 2001; Porges, 2007). Recent accounts have suggested that there is a positive relationship between vagal activity and well-being, typically defined as life satisfaction, high levels of positive emotions, and low levels of negative emotions (e.g., Kok & Fredrickson, 2010; Oveis et al., 2009; Rottenberg, Clift, Bolden, & Salomon, 2007). Here, however, we investigated the possibility that this positive relationship between vagal activity and well-being holds only up to a point and that, at very high levels of vagal activity, vagal activity and well-being may be negatively related to one another. Thus, we tested whether vagal activity is quadratically (inverted-U) related to well-being.

The Case for Cardiac Vagal Tone's Positive Influence on Well-Being

The vagus nerve extends from the brainstem and innervates numerous organs involved in emotions and social functioning, including the heart, select facial muscles, larynx, soft palate, pharynx, esophagus, and bronchi (Beauchaine, 2001). Theoretical models hold that the vagus nerve promotes flexibility to adapt to an ever-changing environment (Porges, 2001; Porges, 2007; Rottenberg et al., 2007). One critical pathway for accomplishing this is through regulation of the heart; in particular, vagus nerve activity promotes a decrease in heart rate, functioning as a vagal brake. Vagal control over the heart is reflected in measures of cardiac vagal tone (CVT), which is typically quantified as respiratory sinus arrhythmia (RSA) or heart rate variability over the breathing cycle (Beauchaine, 2001). Research has linked CVT to many psychological and biological processes, including attention (Hansen, Johnsen, & Thayer, 2003), self-regulation (Bornstein & Suess, 2000), exercise (Dixon, Kamath, McCartney, & Fallen, 1992), respiration (Grossman & Kollai, 1993), and sleep (Vanoli, Adamson, Pinna, Lazzara, & Orr, 1995). Many of these processes likely contribute to people's well-being. Thus, CVT is likely not directly related to well-being per se, but rather via these psychological and physiological processes.

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In line with the theoretical and anatomical evidence, research has suggested that greater CVT is positively related to well-being. For instance, low CVT levels are markers of numerous mental illnesses, including major depressive disorder (Dalack & Roose, 1990; Rottenberg et al., 2007), anxiety (Friedman & Thayer, 1998), and posttraumatic stress disorder (Cohen, Kotler, Matar, & Kaplan, 1997). Furthermore, CVT in children is associated with greater sociability (Eisenberg et al., 1995). Among adults, greater CVT predicts more social connectedness (Kok & Fredrickson, 2010) and greater agreeableness (Oveis et al., 2009). Higher CVT levels are also generally correlated with increased positive emotions (Kok & Fredrickson, 2010; Oveis et al., 2009) and decreased depressive symptoms (Beauchaine, 2001; Rottenberg et al., 2007).

Is Greater CVT Better?

At first glance, these findings could be interpreted to indicate that greater CVT predicts higher levels of well-being. But is more of a good thing *always* better in the case of CVT? A closer look at the research on CVT and well-being suggests that the link between CVT and well-being may not be an unmitigatedly positive one. For instance, the evidence for the link between CVT and depression is mixed (Rottenberg, 2007), with some studies finding a negative relationship between CVT and depression (e.g., Rottenberg, Wilhelm, Gross, Biuckians, & Gotlib, 2001), others failing to find any relationship at all (e.g., Volkers et al., 2004), and one study even finding a positive link between CVT and depression. Other work has documented that, among adolescent girls, there is a *negative* link between CVT and social functioning (Eisenberg et al., 1995), and one study found that greater CVT was related to more negative emotions in adults (Kok & Fredrickson, 2010). Two potential explanations for the lack of consistency in the findings are methodological concerns and sample biases (Rottenberg, 2007), such as lack of proper controls for potential confounds (e.g., respiration) or sampling participants within a restricted range of CVT values.

Here, we investigated a third possibility: that some of these inconsistent findings may be explained by a nonlinear relationship between CVT and well-being. In particular, we speculated that the relationship between CVT and well-being may be quadratic (inverted-U) such that individuals with moderate CVT exhibit higher levels of well-being than individuals with either very low or, crucially, very high CVT. Although this third potential reason is not mutually exclusive from methodological or sampling biases, it provides a distinct theoretical possibility that can be tested within a single study where sampling and methodology is constant. To date, no study has explicitly tested whether a quadratic model describes the relationship between CVT and well-being more accurately than a linear model. To provide a robust test of our predictions, we examined vagal tone and three different measures of well-being (i.e., life satisfaction, global functioning, and depression symptoms) in a large community sample.

Method

Participants

We recruited 231 adults (M_{age} = 40.02 years, SD = 11.14; 52% female; 84% White) from the Denver area community to participate in this study.

Cardiac Vagal Tone and Respiratory Rate

CVT was assessed as heart rate variability within the high-frequency band (range: 0.15–0.50 Hz) during a 2-min neutral film clip in which a male instructor demonstrates how to build sandcastles. This film clip has been used for similar purposes in other research (Shallcross, Ford, Floerke, & Mauss, 2013). Like others (Butler, Wilhelm, & Gross, 2006), we used an emotionally neutral film clip rather than a no-task baseline to assess CVT because minimally demanding tasks provide better estimates of resting cardiovascular activity (Jennings, Kamarck, Stewart, Eddy, & Johnson, 1992). Others have successfully used 2-min or shorter neutral film clips to assess baseline CVT (Rottenberg, Salomon, Gross, & Gotlib, 2005; Rottenberg, Wilhelm, Gross, & Gotlib, 2003), suggesting that two minutes are sufficient.

CVT was computed using heart period scores from Lead-II electrocardiographic signals (Biopac Systems, Santa Barbara, CA) converted into time-series data with a 4-Hz resolution. The time-series data were then linearly detrended and quantified with a power spectral analysis using the Welch method of spectral averaging (cf. Butler et al., 2006). CVT was calculated as the natural logarithm of the power spectral density values within the high-frequency band (Berntson, Norman, Hawkley, & Cacioppo, 2008). CVT values ranged from 2.93−9.80 ms^2 (M = 6.69 ms^2, SD = 1.28). We excluded one participant with a CVT value of more than 3 SD from the mean. See the supplemental materials for details on analyses (a) with all data points, (b) with only one outlier removed, and (c) with a potential second outlier removed. The supplemental materials also discuss several control analyses.

Respiration was assessed using a TSD201 inductive plethysmography device (Biopac Systems, Goleta, CA), which measures the changes in abdominal circumference that occur as the participant breathes. Respiratory rate was computed as the number of breaths per second. Respiration data was available for 227 participants, of which 214 fell within the .15−.50 Hz frequency band. Electrocardiographic and respiration signals were sampled at 1000 Hz. Both signals were edited, scored, and reduced using ANSLAB software, a customized physiological scoring software package (Wilhelm, Grossman, & Roth, 1999).

Well-Being

In an online survey done 1 week before the CVT lab session, participants completed three measures of well-being: (a) life satisfaction was measured using the 5-item Satisfaction With Life Scale (Diener, Emmons, Larsen, & Griffin, 1985), rated on a 1 (*strongly disagree*) to 7 (*strongly agree*) scale (α = .92, M = 3.74, SD = 1.66); (b) global functioning was measured using a 23-item modified self-report version of the Global Assessment of Functioning Scale (American Psychiatric Association, 1994), rated on a 1 (*lowest level*) to 100 (*highest level*) scale (α = .89, M = 143.42, SD = 24.71); and (c) depression symptoms were measured using the Beck Depression Inventory (Beck & Steer, 1984), a 21-item measure of somatic, cognitive, and affective symptoms of depression, rated on a 0−3 scale (α = .93, M = 10.41, SD = 9.30). Graphical inspection revealed that the depression scores were heavily skewed toward low values. This was corroborated by a Shapiro−Wilk normality test (W = .88, p < .001). Thus, we transformed the depression scores by adding 1 to all values and taking the natural logarithm. The resultant transformed variable showed a more normal distribution; thus, we used the log-transformed depression scores for all analyses.[1]

Results

We tested the possibility that the relationship between CVT and well-being could be more accurately described with a quadratic rather than a linear model. To begin, we tested a linear relationship between CVT and our three measures of well-being. We found that CVT was unrelated to life satisfaction, $b = .09$, 95% confidence interval (CI) [−.08, .26], $t(229) = 1.03$, $p = .302$, or depression, $b = -.06$, 95% CI [−.17, .04], $t(229) = -1.24$, $p = .217$. There was also a marginally positive relationship between CVT and global functioning, $b = 2.36$, 95% CI [−0.19, 4.91], $t(213) = 1.83$ $p = .069$. Thus, in our study, there was little evidence for a linear relationship between RSA and well-being.

To test whether CVT was quadratically associated with well-being and whether the quadratic model would present a better fit than the linear model, we entered both the linear and the quadratic CVT terms (centered on the mean) as predictors into our regression models, with our three well-being measures as outcomes. The linear terms in this model were virtually identical to those for the linear models because CVT was centered.

As Figure 1 shows, we found support for the superiority of the quadratic model for all well-being measures. Specifically, CVT was quadratically related to life satisfaction, $b = -.14$, 95% CI [−.24, −.03], $t(228) = -2.63$, $p = .009$, global functioning, $b = -1.58$, 95% CI [−3.11, −0.04], $t(228) = -2.03$, $p = .044$, and depression, $b = .09$, 95% CI [.02, .14], $t(228) = 2.78$, $p = .005$. The relationships between CVT and life satisfaction and global functioning were positive at low CVT values, but increasingly flattened out until curving negatively at high values of CVT. CVT was negatively related to depression at low CVT values, but also eventually flattened out before curving positively at high CVT values. Because all these models included the original linear term, the significant quadratic effects indicate that the quadratic models better captured the relationship between CVT and well-being than the linear models. All results held when controlling for age, sex, and study time of day.

We should note, however, that additional analyses examining the effects of outlier removal (see supplemental materials for full details) showed that the quadratic effect for global functioning dropped below traditional levels of significance when either (a) no outliers or (b) two most extreme cases were removed. The effects for life satisfaction and depression remained significant regardless of outlier approach. Thus, we suggest interpreting the evidence for a quadratic link between CVT and global functioning as null-to-weak, whereas there is strong evidence for a quadratic link between CVT and life satisfaction and depression.

Beyond documenting that the relationship between CVT and well-being is best described as quadratic, we were interested in testing whether individuals with moderate CVT (e.g., average CVT) had better well-being than those with very low or very high CVT. To test this question, we first created two new versions of each outcome variable: The first was centered on the value of the outcome when CVT was low (2 *SD* below the mean) and the second was centered on the value of the outcome when CVT was high (2 *SD* above the mean). We chose to center the outcomes at ± 2 *SD* because this would allow us to compare the three values of interest (low, mean, and high) at 2 *SD* intervals—the same interval that is standard for comparing simple slopes within interactions (typically with one line at −1 *SD* and the other at +1 *SD*, making for a 2 *SD* difference).

Then, we ran two models for each outcome. In each model, both the linear and the quadratic terms of the centered CVT variable served as predictors. The two models differed, however, in the outcome: For the first model, the low version of the outcome was the outcome; for the second version, the high version of the outcome was the outcome. Thus, the intercept of each model represented the difference in the outcome between individuals who were low (Model 1) or high (Model 2) in CVT and individuals who had average CVT. Based on this approach, individuals with moderate CVT (at the peak of the curve) exhibited greater well-being across all three measures than individuals low or high in CVT. Specifically, individuals at the peak of the curve had higher life satisfaction than individuals high in CVT, $b = .66$, 95% CI [.39, .93], $t(228) = 4.85$, $p < .001$, or low in CVT, $b = 1.10$, 95% CI [0.83, 1.37], $t(228) = 8.07$, $p < .001$. Similarly, individuals at the peak of the curve had higher global functioning than individuals high in CVT, $b = 4.38$, 95% CI [0.20, 8.55], $t(212) = 2.07$, $p = .040$, or low in CVT, $b = 16.14$, 95% CI [11.97, 20.31], $t(212) = 7.63$, $p < .001$. Finally, individuals at the peak of the curve had lower depression than individuals high in CVT, $b = -.40$, 95% CI [−.56, −.24], $t(228) = -4.89$, $p < .001$, or low in CVT, $b = -.72$, 95% CI [−.88, −.56], $t(228) = -8.76$, $p < .001$. We should note that these analyses compared average CVT to low and high values; however, we would not necessarily expect that precisely average CVT is optimal. Indeed, it is likely that the optimal level of CVT is between moderate and high values.

Discussion

The present study provides support for the notion that the relationship between CVT and well-being may not be linear but rather quadratic. Our predictions were supported in a diverse sample of participants, and for both positive (life satisfaction) and negative (depressive symptoms) facets of well-being. However, we found only null-to-weak support for a quadratic link between CVT and global functioning. Secondary analyses revealed that individuals with moderate CVT exhibited greater well-being than individuals with either low or high CVT. For life satisfaction and depression, a quadratic model was superior to a linear model in capturing the link between CVT and well-being, regardless of which approach we took to remove outliers. Indeed, there was little evidence for a linear relationship between CVT and any of our

[1] We also conducted all analyses with the non-log-transformed version of depression. The conclusions from the effects were identical for these analyses when removing the most extreme outlier (primary analyses throughout the report). However, the effects on the non-log-transformed version of the variable dropped outside of traditional levels of significance when (a) not removing any outliers or (b) removing a second potential outlier (see supplemental materials for details on outlier removal). We should note, however, that the non-log-transformed version of depression posed serious problems for regression models because of the extreme skewness; thus, the log-transformed models were statistically more appropriate.

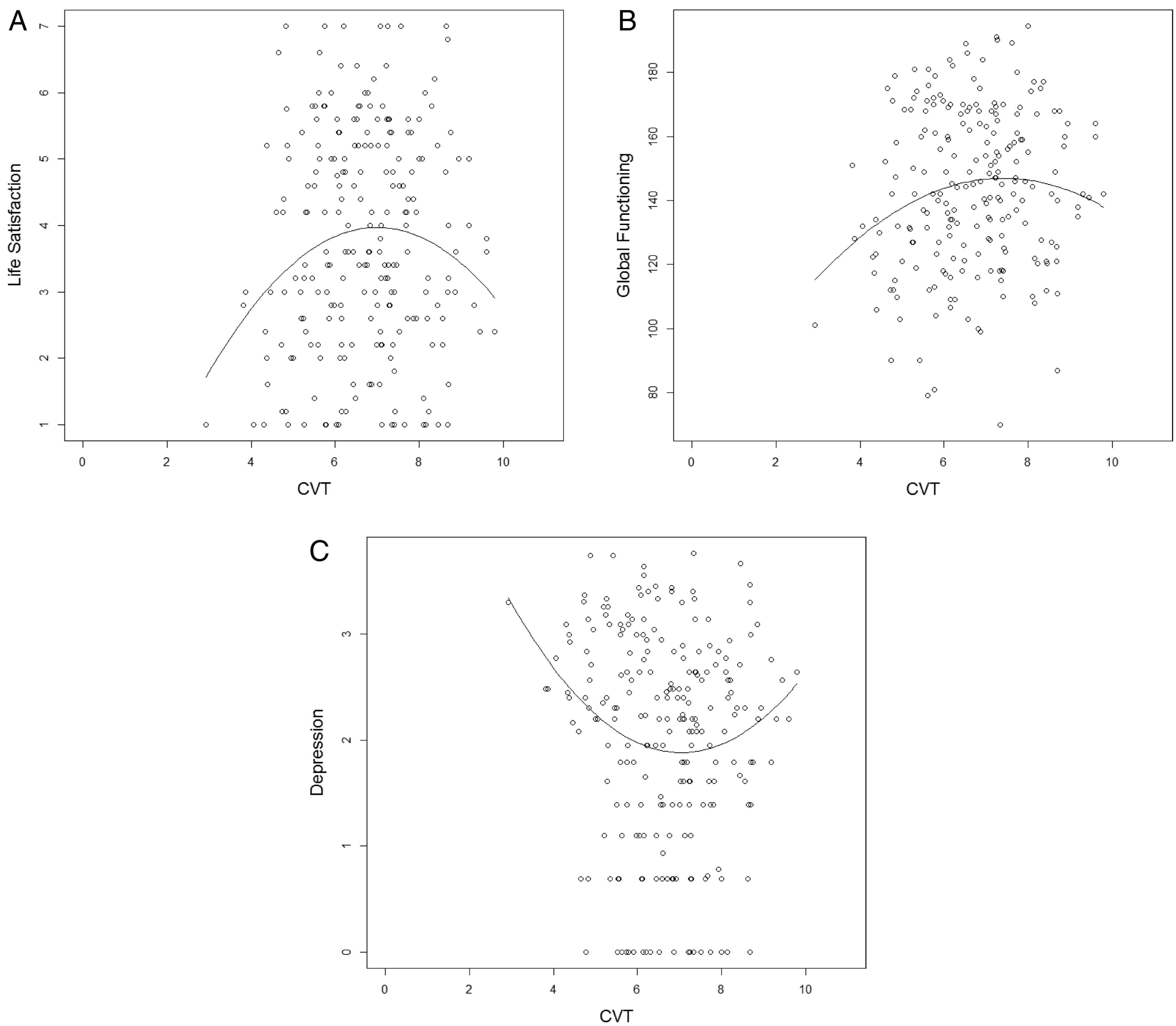

Figure 1. The figures depict the quadratic curves from the regression values for each of our three models. In all three panels, the curve ranges from the smallest to largest value in our sample. Scatterplot of the actual data is presented behind each curve. Please note that in all figures, the most extreme outlier has been removed since his/her CVT value was more than 3 SDs from the mean.

three measures of well-being. In contrast, the quadratic pattern was consistent across two of the three measures of well-being.

Given the wide range of well-being outcomes we measured, these findings have important implications for psychological health. In particular, our findings are consistent with the notion of optimal balance (Fredrickson & Losada, 2005; Schwartz et al., 2002). Optimal balance is typically viewed as the proper mixture of positive to negative emotions—in particular, experiencing some negative emotions is viewed as beneficial for flourishing because such emotional shifts help to maintain affective flexibility. Our results suggest that a similar principle may be in play for CVT.

One reason previous work found a positive link between CVT and well-being may be due to the portion of the CVT distribution being sampled. Studies that examined the low-to-moderate range of CVT would have found a linear link between CVT and well-being, while studies that examined the moderate-to-high range of CVT would have found no or even negative linear relationships. For example, previous work has found that, for adolescent boys (who have lower CVT than girls), there is a positive link between CVT and sociability; however, for adolescent girls, CVT was negatively associated with sociability (Beauchaine, 2001).

Our data showed some inconsistency across the three measures of well-being. In particular, the quadratic relationship between CVT to life satisfaction and depression was robust—the effects were consistently significant whether or not we chose to remove no outliers, one outlier, or two outliers. In contrast, although we found a quadratic link between CVT and global functioning when we removed one outlier from our data, the effect dropped below traditional significance levels when we excluded no outliers or two outliers—we encourage interested readers to examine our supplemental materials in which we present histograms of CVT, our procedure for the selection of outliers, and details of all results when (a) no outliers were removed, (b) one outlier was removed, and (c) two outliers were removed. There are several potential reasons for this inconsistency. First, chance variance could have played a role: The effect of global functioning may simply be dampened by chance fluctuations and error in the scores. Second, our sample was of a nonclinical nature, yet global functioning is typically assessed in the clinical context. Thus, our sample could have created issues in the validity of the scores. We should note that our depression measure was of a clinical nature, but it still showed consistently significant results. Clearly, further work is necessary to examine which of these possibilities—or potentially others—best explains the inconsistency.

Is there a plausible mechanism for diminishing returns—or even a negative effect—of extremely high (compared to moderate) CVT? One possibility centers on the relationship between CVT and social engagement. Vagus nerve activation is theorized to promote greater ability to attend to the needs of others and modulate one's own responses based on those needs, which in turns helps individuals have better social relationships—and thus promotes greater well-being (Porges, 2007). Arguably, social engagement may result in negative outcomes at very high levels. For instance, too much social engagement may lead individuals to cross interpersonal boundaries and attempt to affiliate with others indiscriminately, resulting in others distancing themselves from the individual and consequently reducing the individuals' well-being (Clark & Lemay, 2010). Consistent with this notion, individuals who suffer from mania show just this pattern of unhealthy social engagement (Beigel & Murphy, 1971), as well as increased CVT (Gruber, Johnson, Oveis, & Keltner, 2008). Social engagement is thus one plausible mechanism by which CVT might be linked in a quadratic fashion to well-being. It should be noted, however, that we cannot conclude from our data whether the vagus nerve is causally related to well-being. It is also possible that CVT is a marker of other neurobiological activity and processes that are driving well-being, and that CVT is the effect of well-being and related processes. Most likely, the link between CVT and well-being is bidirectional, with both influencing one another (Kok & Fredrickson, 2010). Future research should explore these possibilities to better understand the mechanism behind the quadratic effects documented here.

More broadly, our results add to a growing body of research that suggests biological and psychological systems often have complex relationships with well-being. For instance, recent evidence has suggested that oxytocin—once dubbed the love hormone—can, under some circumstances, lead to greater jealousy and other negative consequences (Bartz, Zaki, Bolger, & Ochsner, 2011). Other work has documented that happiness can have negative effects at extremely low and at extremely high levels (Gruber, Mauss, & Tamir, 2011). Our findings add to this literature by demonstrating lower well-being for people with extremely high vagus nerve activity compared to individuals with more moderate levels of vagus nerve activity. It seems that, when it comes to cardiac vagal tone, there can be too much of a good thing.

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