Research Article

Heart Rate Variability Reflects Self-Regulatory Strength, Effort, and Fatigue

Suzanne C. Segerstrom and Lise Solberg Nes

University of Kentucky

ABSTRACT—*Experimental research reliably demonstrates that self-regulatory deficits are a consequence of prior self-regulatory effort. However, in naturalistic settings, although people know that they are sometimes vulnerable to saying, eating, or doing the wrong thing, they cannot accurately gauge their capacity to self-regulate at any given time. Because self-regulation and autonomic regulation colocalize in the brain, an autonomic measure, heart rate variability (HRV), could provide an index of self-regulatory strength and activity. During an experimental manipulation of self-regulation (eating carrots or cookies), HRV was elevated during high self-regulatory effort (eat carrots, resist cookies) compared with low self-regulatory effort (eat cookies, resist carrots). The experimental manipulation and higher HRV at baseline independently predicted persistence at a subsequent anagram task. HRV appears to index self-regulatory strength and effort, making it possible to study these phenomena in the field as well as the lab.*

A number of problems of modern life stem from failures of self-regulation, the ability to control one's own thoughts, emotions, and behavior. Failure to inhibit the impulse to eat is in part responsible for obesity, for example, and failure to control anger can result in interpersonal aggression. Many such failures are unplanned; that is, they are lapses of self-regulation rather than intended acts. Why do people act contrary to their intentions? Experimental evidence indicates that self-regulatory strength—the ability to meet self-regulatory demands such as inhibiting impulses, making decisions, persisting at difficult tasks, and controlling emotions—is a resource that can be spent. In a series of studies, expending self-regulatory strength by eating undesirable foods in the presence of desirable foods, making choices, and suppressing thoughts or emotions created subsequent deficits in persistence at and performance on cognitive and motor tasks (Baumeister, Bratslavsky, Muraven, & Tice, 1998; Muraven, Tice, & Baumeister, 1998). Self-regulatory strength may therefore be analogous to muscle strength: The more effort is expended, the more the self-regulatory "muscle" is fatigued, and the less strength remains for further efforts (Muraven & Baumeister, 2000). This fatigue can lead to lapses of self-regulation.

A difference between muscle fatigue and self-regulatory fatigue, however, is that people are not aware of self-regulatory fatigue. People do not report substantial differences in their appraisals of tasks that require self-regulatory effort versus tasks that do not, nor do they report differential affective consequences of those tasks (Baumeister et al., 1998; Muraven et al., 1998). Without an index of self-regulatory strength and fatigue—an electromyograph for the self-regulatory muscle—the concept of self-regulatory strength is difficult to apply empirically to naturalistic settings, in which a failure of self-regulation (e.g., eating a doughnut while on a diet) could be construed both as the indicator of self-regulatory fatigue and as the consequence of that fatigue. Unraveling this tautology requires the ability to measure how much self-regulatory strength people have available, how much self-regulatory effort they are expending, and whether they are vulnerable to the negative consequences of self-regulatory fatigue.

A measure of parasympathetic control over the heart, heart rate variability (HRV), offers just such an opportunity. Parasympathetic input to the heart via the efferent vagus nerve affects heart rate acceleration and deceleration related to respiration: The heart speeds up after inspiration and slows down after expiration. More parasympathetic input results in more pronounced acceleration and deceleration and more variable intervals between heart beats, that is, higher HRV. HRV is a

Address correspondence to Suzanne C. Segerstrom, Department of Psychology, University of Kentucky, 115 Kastle Hall, Lexington, KY 40506-0044, e-mail: scsege0@uky.edu.

likely candidate to index self-regulatory capacity and activity because brain structures involved in self-regulation and those involved in autonomic nervous system regulation overlap considerably, particularly with regard to the prefrontal cortex. Self-regulatory tasks are associated with activation of prefrontal cortex, and self-regulatory fatigue adversely and selectively affects performance on cognitive tasks that are considered to be frontal or executive (Schmeichel, Vohs, & Baumeister, 2003; Small, Zatorre, Dagher, Evans, & Jones-Gotman, 2001). Prefrontal cortices form part of the *central autonomic network* (CAN), which also includes the anterior cingulate, insula, amygdala, hypothalamus, and periaqueductal gray (Thayer & Lane, 2000). The CAN is in part responsible for parasympathetic input to the heart, as demonstrated by a decrease in HRV after cortical anesthesia (Ahern et al., 2001).

We predicted that self-regulatory effort would covary with HRV, such that higher HRV would reflect greater self-regulatory effort. Because the CAN and structures essential to self-regulation colocalize in the brain, the cortical activity that accompanies self-regulation should also result in increased vagal input to the heart. Our first hypothesis, therefore, posited higher HRV during high self-regulatory effort compared with low self-regulatory effort. We further expected that tonic self-regulatory strength or capacity should be reflected in higher tonic HRV. Higher resting HRV has been associated with a number of potential indicators of self-regulatory capacity, including better performance on executive cognitive tasks, less negative emotion during daily stress, more effective coping with stress, and better impulse control (Allen, Matthews, & Kenyon, 2000; Fabes & Eisenberg, 1997; Hansen, Johnsen, & Thayer, 2003; Johnsen et al., 2003). Our second hypothesis, therefore, stated that higher resting HRV should predict later self-regulatory capacity. Finally, we hypothesized that the subjective and physiological effects of high self-regulatory effort would differ from those of a typical laboratory stress activity. Specifically, we expected high self-regulatory effort to be differentiated from low self-regulatory effort not by subjective response, but by higher HRV; in contrast, a typical laboratory stress activity would be differentiated from a low-stress activity by a marked subjective response and lower HRV.

METHOD

Subjects

University students signed up for a study of the physiology of "food preferences" that ostensibly compared physiological reactions to different foods with physiological reactions to stress and relaxation. Mean age of the 168 subjects was 19.1 years (range = 18–27). The ethnic-racial distribution was consistent with the demographic makeup of the university; the majority (89%) of the subjects were Caucasian, 9% were African American, 1% were Asian American, and 1% were of other backgrounds. Men (47%) and women (53%) participated in roughly equal proportions. Subjects received partial credit toward a course requirement.

Procedure

Self-Regulation Conditions

We experimentally manipulated self-regulatory effort by having subjects either resist or indulge in desirable foods (chocolate and cookies) and then measured their further ability to self-regulate, specifically, to persist at a difficult anagram task. Subjects were randomly assigned to two conditions. All subjects, who had fasted for the previous 3 hr, were presented for 5 min with a tray holding carrot sticks, warm chocolate-chip cookies, and chocolate candies in separate compartments. In the low-self-regulation condition ($n = 42$), subjects were instructed to eat only the cookies or candies, but not the carrot sticks. In the high-self-regulation condition ($n = 41$), they were instructed to eat only the carrot sticks, but not the cookies or candies. All subjects were compliant with the experimental instructions.

As a manipulation check, food desirability was measured with three items with Likert-type response scales ("How much did you want to eat the food you just ate?" "How hard did you have to try to keep eating the food you just ate?" "How much would you like to eat more of the food you just ate?") and four bipolar items ("The food I just ate was . . . desirable-undesirable," ". . . satisfying-unsatisfying," ". . . disgusting-delicious," ". . . my favorite-my least favorite"). Other bipolar filler items (with choices of "unfamiliar-familiar," "sweet-bitter," "strong-tasting–mild-tasting") were included to bolster the ostensible rationale for the study. Cookies and chocolate were rated significantly more desirable than carrots, $F(1, 78) = 9.21$, $p_{rep} = .97$, $\eta = .32$. The possibility that there were sex differences in food desirability was also tested, but although women tended to find carrots more desirable than did men, there was not a significant interaction between gender and food desirability, $F(1, 78) = 2.11$, $p_{rep} = .77$, $\eta = .16$.

Following the experimental manipulation, subjects were asked to solve a number of moderately difficult to impossible anagrams. They were given up to 5 min to work on an unsolvable anagram and up to 90 s each to work on 10 additional difficult but solvable anagrams. Time before giving up on or solving each anagram was measured by the experimenter with a stopwatch. To control for effects of total task time on physiological states during the anagram task and recovery, we required all subjects to go back and work on unsolved anagrams up to the total task time of 20 min. Evidence for self-regulatory fatigue was operationalized as decreased persistence at the first, unsolvable anagram and at all anagrams in the first round only (i.e., the time before voluntarily giving up on all anagrams). All subjects then rested quietly for 30 min.

Subjective ratings of mood and task appraisals were obtained by questionnaire. The mood measure was administered after each experimental period (resting baseline, food, anagrams, and rest). It included 25 items from the Positive and Negative Affect Schedule–Expanded Form (Watson & Clark, 1994), specifically, the subscales for Negative Affect, Positive Affect, Fatigued Affect, and Attentive Affect. Task appraisals were measured with six items with Likert-type response scales ("It was difficult," "It was stressful," "It required a lot of effort," "I had to concentrate on the task," "I had to force myself to keep going," "I wanted to stop before it was over"); these items were administered after the food and anagram tasks. Alpha reliability for the six items was .93 after the food task and .81 after the anagram task. We also measured public self-consciousness (Fenigstein, Scheier, & Buss, 1975), because this personality trait increases motivation to perform well in front of other people (e.g., an experimenter) and therefore increases persistence at the anagram task (Solberg Nes, Segerstrom, & Sephton, 2005).

Psychophysiological readings were taken using an Ambulatory Monitoring System (Vrije Universiteit, Amsterdam, The Netherlands) with heart rate leads attached to the chest in a Lead II configuration and skin-conductance leads attached to the middle medial phalanges of the nondominant hand. Skin-conductance level (SCL) was measured using Ag-AgCl electrodes and electrode paste with physiologic concentration of electrolytes. The electrocardiogram was sampled at 1,000 samples/s, and beats per min and mean squared successive differences in the interbeat interval (HRV) were calculated on-line and stored in 30-s epochs. SCL was sampled at 1,000 samples/s and stored in 1-s epochs. Heart rate (HR; beats per minute), HRV (measured as the root mean squared successive differences in the interbeat interval; Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996), and SCL (micromhos) were measured continuously.

Stress Conditions

We compared the consequences of the manipulation of self-regulatory effort with the consequences of a typical stress manipulation by randomly assigning additional subjects to either high ($n = 43$) or low ($n = 42$) stress instead of self-regulation. In the high-stress condition, instead of performing a self-regulation task, subjects recited patriotic texts for 5 min as quickly as they could; an experimenter made standardized critical comments over a loudspeaker at specified times. Public-speaking tasks are commonly used to study psychophysiological stress reactivity, including changes in HRV, so we chose this task to provide a comparison condition for stress as it is commonly operationalized in psychophysiology research (e.g., Burleson et al., 1998; Farag, Bardwell, Nelesen, Dimsdale, & Mills, 2003; Hughes & Stoney, 2000). In the low-stress condition, subjects were asked to relax for 5 min, instead of performing a self-regulation task. Otherwise, the tasks and methods were as described for the self-regulation conditions.

Data Analysis

Subjective and behavioral consequences of the experimental manipulations were tested using repeated measures analysis of variance. Within-subjects analyses employed the Huynh-Feldt correction to degrees of freedom for departures from sphericity as indicated by epsilon values. Persistence was predicted using hierarchical regression models with dummy codes for experimental condition; continuous predictors were centered before analysis.

RESULTS

Subjective and Behavioral Consequences of Self-Regulatory Effort and Fatigue

The effect of high and low self-regulatory effort on subjective experience was minimal. Eating carrots was perceived as being slightly but significantly more difficult, stressful, and effortful than eating cookies ($M = 1.69$, $SD = 1.05$, vs. $M = 1.20$, $SD = 0.30$, on a scale from 1 to 5), $F(1, 81) = 8.25$, $p_{rep} = .97$, $\eta = .30$, but high and low self-regulatory effort did not differ significantly in their effects on negative mood, positive mood, attentiveness, or subjective fatigue during the food task or across all tasks (all Fs < 1, all ηs $\leq .11$).

Nonetheless, self-regulatory effort affected subsequent persistence. Figure 1 shows the effect of self-regulation condition and self-consciousness on persistence at the first, unsolvable anagram (i.e., self-regulatory fatigue). Although self-consciousness is ordinarily associated with increased persistence on the anagram task (Solberg Nes et al., 2005), this persistence was absent among subjects who had previously exercised high self-regulatory effort, as reflected in a significant interaction between self-consciousness and self-regulation condition, $B = -37.2$, $SE = 8.2$, $t(77) = -4.54$, $p_{rep} > .99$, $pr = .42$. This

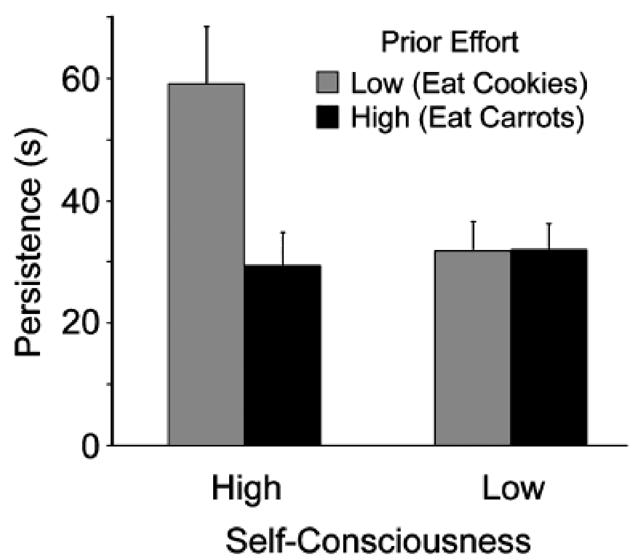

Fig. 1. Effects of prior self-regulatory effort on persistence at the first, unsolvable anagram in subjects above and below median self-consciousness. Means are shown with standard errors.

interaction moderated significant main effects of both self-consciousness, $B = 14.1$, $SE = 4.6$, $t(77) = 3.09$, $p_{rep} = .97$, and self-regulation condition, $B = -13.9$, $SE = 6.4$, $t(77) = -2.17$, $p_{rep} = .90$; $pr = .41$ for the main-effect step. Therefore, although subjects did not feel effects of self-regulatory fatigue as a result of eating carrots instead of cookies and chocolate, their subsequent lower persistence indicated self-regulatory fatigue. This effect replicates results of a number of other experiments in which high self-regulatory effort caused later deficits in persistence (Baumeister et al., 1998; Muraven & Slessareva, 2003; Muraven et al., 1998). Total time spent on the anagram task showed similar but attenuated effects—interaction between self-consciousness and condition: $B = -122.0$, $SE = 80.3$, $t(77) = -1.52$, $p_{rep} = .78$, $pr = .17$; main effect of self-consciousness: $B = 72.3$, $SE = 40.0$, $t(77) = 1.81$, $p_{rep} = .85$; and main effect of self-regulation condition: $B = -57.1$, $SE = 56.5$, $t(77) = -1.01$, $p_{rep} = .63$; $pr = .24$ for the main-effect step.

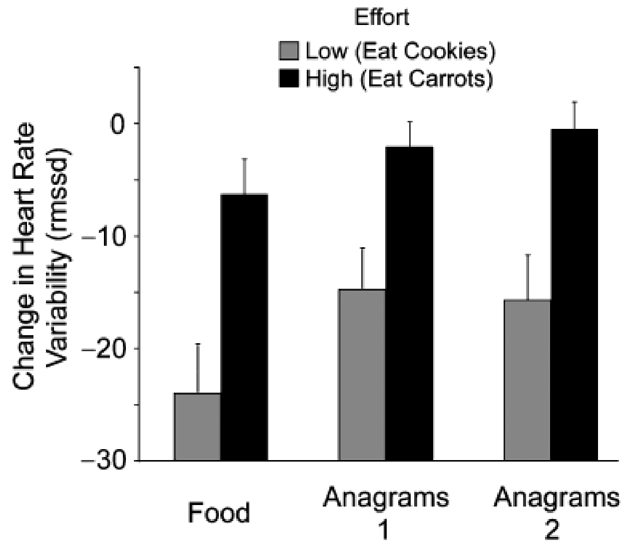

Fig. 2. Change in heart rate variability from baseline as a function of self-regulation condition across the experimental tasks: eating cookies or carrots and then solving anagrams (Rounds 1 and 2). Mean changes are shown with standard errors. rmssd = root mean squared successive differences in the interbeat interval.

Physiological Concomitants and Consequences of Self-Regulatory Effort

A good index of self-regulation should have at least the following two properties: First, it should differentiate tasks that require high self-regulatory effort from tasks that require low effort, much as an electromyograph discriminates between a flexed muscle and one that is relaxed. Second, higher self-regulatory strength should predict better self-regulation, much as a stronger muscle can exert more force.

As predicted, HRV was elevated during high self-regulatory effort relative to low effort, as reflected in a significant interaction of task (i.e., baseline, regulation, anagrams, rest) and self-regulation condition (high vs. low effort), $F(4, 312) = 5.16$, $\varepsilon = .79$, $p < .05$, $\eta = .25$. Figure 2 shows HRV changes from baseline during the food and anagram tasks. During the self-regulation task, subjects eating carrots, that is, those exerting a higher level of self-regulatory effort, had higher HRV relative to baseline than did subjects eating cookies and chocolate. This difference persisted during the first and second rounds of anagrams, although the HRV of the low self-regulation group increased significantly with the transition to the anagram task, $t(41) = 2.63$, $p_{rep} = .94$, $d = 0.41$, an effect consistent with the increased self-regulatory demands of this new task. In contrast, although the HRV of the high-self-regulation group also increased during the first round of anagrams, the increase was slight, and the difference from their HRV during the preceding high-self-regulation task was not significant, $t(40) = 1.24$, $p_{rep} = .71$, $d = 0.19$.

HR and SCL also differed significantly between the high-effort and low-effort self-regulation conditions. Results for HR were consistent with those for HRV; HR was lower during high self-regulatory effort than during low effort, as reflected in a significant task-by-condition interaction, $F(4, 312) = 12.56$, $\varepsilon = .78$, $p < .05$, $B = .27$. There were no skin conductance differences during the food task, but during the anagram task and recovery period, prior high self-regulatory effort was associated with higher skin conductance, as reflected in a significant task-by-condition interaction, $F(4, 312) = 4.91$, $\varepsilon = .72$, $p < .05$, $\eta = .24$. The dissociation between the cardiac measures and skin conductance supports a specific link between self-regulation and cardiac regulation. Controlling for age and gender did not substantively change the results of these analyses.

Finally, if HRV indexes self-regulatory strength as well as effort, then greater tonic or baseline HRV should indicate greater self-control ability and predict later persistence. This was, in fact, the case. Higher HRV during the baseline period predicted longer persistence on the first anagram; HRV accounted for an additional 5% of the variance in persistence after controlling for self-consciousness, $B = 0.013$, $SE = 0.006$, $t(80) = 2.14$, $p_{rep} = .90$, $pr = .22$. As shown in Figure 3, higher HRV also predicted longer persistence on the first round of anagrams, $B = 1.56$, $SE = 0.74$, $t(80) = 2.10$, $p_{rep} = .89$, $pr = .22$. HRV during the anagram task also predicted persistence, but not after accounting for baseline differences in HRV; that is, subjects with higher HRV during baseline also had higher HRV during the anagram task and also persisted longer at the task. Controlling for self-regulation condition and self-consciousness slightly reduced the effect of HRV on persistence at the first anagram and at all anagrams, but the reduction was particularly slight for persistence at all anagrams (first anagram, $pr = .16$; all anagrams, $pr = .21$).

Is Self-Regulation Nothing More Than Stress?

As predicted, the effects of a common laboratory stress manipulation were quite different from those of self-regulation.

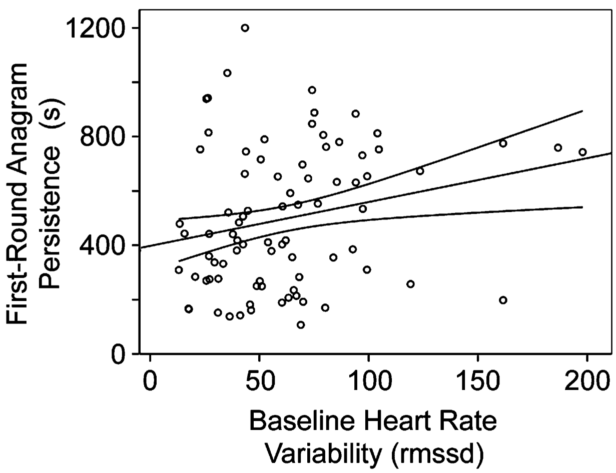

Fig. 3. Persistence at the anagram task as a function of baseline heart rate variability. The solid lines indicate the regression line and 95% confidence intervals. rmssd = root mean squared successive differences in the interbeat interval.

Although subjects were unaware of self-regulatory effort and fatigue, they were subjectively aware of stress. The speech task was perceived as being much more difficult, stressful, and effortful than the relaxation task (M = 2.98, SD = 0.80, vs. M = 1.21, SD = 0.59), $F(1, 83) = 133.61$, $p_{rep} > .99$, $\eta = .79$. The speech task was also more affectively arousing than the relaxation task. Compared with the relaxation task, the speech task was characterized by significantly higher negative affect, $F(1, 83) = 10.10$, $p_{rep} = .98$, $\eta = .33$; positive affect, $F(1, 83) = 25.82$,$p_{rep} > .99$, $\eta = .49$; and attentive affect, $F(1, 83) = 53.48$, $p_{rep} > .99$, $\eta = .63$. Affect during the other tasks did not differ between the high- and low-stress conditions, resulting in significant task-by-condition interactions for negative affect, $F(3, 249) = 4.80$, $\varepsilon = .76$, $p_{rep} = .96$, $p < .05$, η= .23; positive affect, $F(3, 249) = 3.60$, $\varepsilon = .88$, $p_{rep} > .99$, $p < .05$, $\eta = .20$; and attentive affect, $F(3, 249) = 17.08$, $\varepsilon = .95$, $p_{rep} > .99$, $p < .05$, $\eta = .41$. Although fatigue did not differ significantly between conditions during the stress task, $F(1, 83) = 2.57$, $p_{rep} = .80$, $\eta = .17$, there was a significant task-by-condition interaction, $F(3, 249) = 2.12$, $\varepsilon = .97$, p_{rep} = .96, $p < .05$, $\eta = .16$, that reflected lower fatigue during the speech task than during the relaxation task and higher fatigue afterward.

Also unlike the self-regulation manipulation, the stress manipulation did not result in subsequent differences in persistence. There was no main effect of stress condition or interaction between condition and self-consciousness on persistence at the first anagram or all anagrams (all $p$rs < .10).

Finally, the physiological concomitants of stress differed from those of self-regulation. Speaking was associated with lower HRV, higher HR, and higher SCL than was relaxing, but there were no significant differences between conditions during other tasks. All task-by-stress-condition (high vs. low stress) interactions were significant—HRV: $F(4, 320) = 10.85$, $\varepsilon = .83$, $p_{rep} > .99$, $p < .05$, $\eta = .35$; HR: $F(4, 320) = 59.42$, $\varepsilon = .67$, $p_{rep} > .99$, $p < .05$, $\eta = .65$; and SCL: $F(4, 320) = 4.00$, $\varepsilon = .70$, $p_{rep} = .95$, $p < .05$, $\eta = .22$. These effects are consistent with results of previous investigations into the effects of speech stress on HRV in particular and autonomic change in general (e.g., Burleson et al., 1998; Farag et al., 2003; Hughes & Stoney, 2000). Controlling for age and gender did not substantively change the results of these analyses.

Therefore, self-regulation differed from stress in three important ways: Self-regulatory effort and fatigue were not well described by subjective difficulty, stress, or mood, whereas stress was; self-regulatory effort and fatigue resulted in later persistence deficits, whereas stress did not; and self-regulatory effort and fatigue were accompanied by higher HRV and lower HR and afterward by increases in SCL, whereas stress was accompanied by lower HRV, higher HR, and higher SCL, but no differences afterward.

DISCUSSION

People are aware that they are sometimes vulnerable to saying the wrong thing, eating the wrong thing, or doing the wrong thing, but they may be unaware of their own self-regulatory capacity at any given time. A colleague of ours offered an example from her own life. She knows that when coping with the demands of her four small children, she will lose her patience with them at some point, but she is not aware of the process by which she arrives at that point or when it will arrive. The present results show, however, that her self-regulatory efforts and their likelihood of failure are not completely invisible: They are reflected in her HRV. It is unlikely that our colleague will begin wearing a cardiac monitor to evaluate whether she is about to lose patience with her children. However, for people facing more serious consequences of self-regulatory failure, HRV feedback could be helpful. Alcoholics who reported that they could typically resist temptations to drink had increases in HRV during experimental exposure to alcohol cues, but their less restrained counterparts did not have these increases, a result suggesting that increased HRV in response to relevant cues is a marker for capacity to resist temptation (Ingjaldsson, Laberg, & Thayer, 2003). HRV feedback could, for example, indicate to a quitting smoker when he or she is becoming more vulnerable to cravings and allow him or her an opportunity to avert temptation before it becomes irresistible. When motivated to do so, people can override self-regulatory fatigue (Martijn, Tenbult, Merckelbach, Dreezens, & de Vries, 2002; Muraven & Slessareva, 2003), and so the timely bolstering of motivation could prevent self-regulatory failure.

Our pursuit of HRV as an index of self-regulation was based on anatomical overlap between brain structures associated with self-regulation and those associated with autonomic inhibition. It may be no accident that there is an association between this index of a parasympathetically mediated inhibitory system and self-regulation. One major task of most organisms is to effectively utilize available energy to meet environmental demands, for example, by redirecting energy to the heart and large muscles during "fight or flight." In contrast to the physical demands of fight or flight, self-regulation usually requires mental effort and is often a matter of *not* acting; under such demands, it may be adaptive to engage the "vagal brake" to reduce energy demands in the periphery, make glucose available for the metabolic costs of mental effort, and promote calm reflection (Fairclough & Houston, 2004; Porges, 2001).

These results also indicate a need to differentiate between stress and self-regulation. Some stressful tasks call for self-regulation, and some self-regulatory tasks may be perceived as stressful, but the effects of these two constructs on appraisal and mood, self-regulatory strength, and physiology differ quite markedly. Mixed tasks—those that combine stress and self-regulation—have yielded perplexing results. For example, Fairclough and Houston (2004) found evidence for increasing HRV over time during a prolonged Stroop task, which was contradictory to their hypothesis that longer stress duration decreases HRV. However, our conceptualization of HRV can explain this result as reflecting increasing recruitment of self-regulatory strength over the course of a stressful task that also requires executive control.

The amount of self-regulatory strength available to resist temptation, persist at difficult tasks, or regulate emotion varies from person to person and from time to time. The availability of an index of self-regulation, HRV, offers the opportunity to evaluate more carefully the self-regulatory demands of tasks, experiences, and interventions, and the ability of individuals to self-regulate. Experimental designs have provided compelling evidence for the presence of self-regulatory fatigue. The reflection of self-regulatory ability, effort, and fatigue in HRV means that by using diary methodology and the like along with ambulatory monitoring of HRV, the study of self-regulatory fatigue can come out of the lab and into the field.

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