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A subtle threat cue, heart rate variability, and cognitive performance

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Abstract

This research was designed to extend the literature on heart rate variability (HRV) in cognitive performance contexts by examining whether a subtle threat cue (the color red) in a test environment influences HRV reactivity and whether HRV reactivity is associated with change in cognitive performance. Thirty-three participants took an IQ test, briefly viewed red or a chromatic or achromatic control color, and then took a parallel form of the IQ test. High frequency (HF)-HRV (often referred to as respiratory sinus arrhythmia), was assessed before and after the color manipulation. Results indicated that participants who viewed red (relative to a control color) exhibited a decrease in HF-HRV and that decreased HF-HRV was associated with worse IQ performance. These findings demonstrate the sensitivity of HRV as an index of effective and efficient emotion regulation in an achievement context.

Descriptors: Red, Color, Heart rate variability, Reactivity, Cognitive performance

Psychologists have long been interested in studying cardiovascular activity in cognitive performance contexts (Hebb, 1955; Yerkes & Dodson, 1908). A popular and powerful indicator of cardiovascular activity in the contemporary literature is heart rate variability (HRV), and recent conceptual work has drawn links between HRV and anxiety (B. H. Friedman, 2007) and HRV and cognitive functioning in test settings (J. F. Thayer, Hansen, Saus-Rose, & Johnsen, 2009). In the present research, we sought to extend the empirical work in this area by examining whether a subtle threat cue (the color red) in an IQ test environment influences HRV reactivity (i.e., change in HRV) and whether HRV reactivity is associated with change in IQ test performance.

HRV is a noninvasive measure of autonomic contributions to cardiac functioning. The high frequency (HF) component of HRV is used most commonly in investigations of HRV and is the primary focus herein (referred to as HF-HRV). HF-HRV is mediated almost exclusively by parasympathetic activity and is viewed as an indicator of cardiac vagal tone (Akselrod et al., 1981; Lane et al., 2009). It is closely related to (and often referred to as) respiratory sinus arrhythmia (RSA), the degree to which heart rate accelerates during inspiration and slows during exhalation (Bernstein et al., 1997; Frazier, Strauss, & Steinhauer, 2004).

Empirical research shows that stressful events, such as tests of cognitive ability, lead to decreased HRV (Hansen, Johnsen, & Thayer, 2003; Lovallo, 2005). Vigilance tasks, working memory tasks, and reaction time tasks, as well as related tasks that tax cognitive resources, are associated with decreases in vagally mediated HRV (J. F. Thayer et al., 2009). In addition, experimental manipulations of anxiety, worry, and fear also produce a decrease in HRV (Kreibig, 2010; J. F. Thayer, Friedman, & Borkovec, 1996). All of this empirical work on aversive affective states and HRV has used explicit manipulations of emotion, such as picture sets, film clips, and guided imagery exercises. Research on "implicit affective cues" (R. S. Friedman & Förster, 2010, p. 875) indicates that certain environmental stimuli carry well-being relevant information, and that simply perceiving such stimuli is sufficient to evoke important psychological and physiological processes (for a review, see R. S. Friedman & Förster, 2010). It remains to be seen whether a subtle threat cue in an achievement situation is sufficient to influence HRV processes.

Elliot and Maier (2007) recently proposed that the color red signals the psychological danger of failure in test situations. Red is used in student evaluation to indicate mistakes and, more generally, in language to represent negative events ("caught red-handed") and in traffic signals, alarms, and sirens to indicate impending danger. These uses of red are presumed to produce learned associations between red and specific forms of danger in situations where negative possibilities are salient. These culturally based associations may themselves be bolstered by or even derived from an evolutionarily engrained predisposition to

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interpret red as a signal of danger in contexts where negative outcomes are salient (e.g., in several species of ape, red signals the dominance or attack readiness of an opponent; Pryke, Andersson, Lawes, & Piper, 2001; Setchell & Wickings, 2005).

If, indeed, red functions as an implicit danger cue, the mere act of perceiving red prior to taking a test should evoke anxiety, worry, and avoidance motivational processes (Moller, Elliot, & Maier, 2009). Several recent experiments have yielded data supporting this hypothesis, as viewing red, relative to other chromatic and achromatic colors, prior to taking a test has led to the selection of easy rather than moderately challenging test items, less knocking on the door of a room where the test would be taken, and an increase in local perceptual focus (indicative of vigilant processing; Elliot, Maier, Binser, Friedman, & Pekrun, 2009; Elliot, Maier, Moller, Friedman, & Meinhardt, 2007; Maier, Elliot, & Lichtenfeld, 2008; see also Lichtenfeld, Maier, Elliot, & Pekrun, 2009). Herein, we used red as a subtle threat cue in the context of an IQ test and examined whether red (relative to chromatic and achromatic control colors) produces a decrease in HRV.

Theorists have posited a link not only between HRV and emotional experience, but also between HRV and prefrontal cortical activity involved in sustained attention and executive function. This takes place at two levels. First, resting levels of vagally mediated HRV are positively associated with cognitive performance (J. F. Thayer et al., 2009). Second, during the performance of cognitive tasks, vagally mediated HRV is decreased relative to resting levels (Hansen et al., 2003). That is, low task-related HRV is not only viewed as reflecting anxiety and worry, but is also thought to reflect mental load (Jorna, 1992; Tattersall & Hockey, 1995) and inefficient and ineffective cognitive functioning (Porges, 1992; J. F. Thayer & Lane, 2000). Thus, low task-related as well as resting levels of vagally mediated HRV should be linked to poor performance on cognitive tasks requiring mental manipulation and flexible cognitive processing. Low task-related HRV may be related to poor cognitive performance because it reflects stress, anxiety, or an excessive strain on cognitive resources, all of which can impair task-relevant processing. Furthermore, the existing research has tended to yield supportive evidence, indicating that resting HRV is positively associated with performance on response inhibition and working memory tasks and thus may be a resource that can be utilized during task performance (Croizet et al., 2004; Hansen et al., 2003; Hansen, Johnsen, Sollers, Stenvik, & Thayer, 2004; Hansen, Johnsen, & Thayer, 2009; Johnsen et al., 2003; Luft, Takase, & Darby, 2009).

The aforementioned research conducted on HRV and cognitive performance has focused on individual differences in HRV or has assessed HRV during task performance. Studies of individual differences in HRV yield valuable information, but are silent with regard to dynamic HRV processes; likewise, studies assessing HRV during task performance yield important insights, but also possess inherent methodological limitations. Specifically, when HRV is assessed at the same time as task performance, it is impossible to discern whether HRV is an antecedent or consequence of variation in task performance, and the physical movement involved in performing the task itself can influence HRV (Lehrer et al., 2010). In the present research, we focused on the link between state HRV, assessed independently of and prior to task engagement, and performance on the working memory component of an IQ test, a task requiring mental manipulation and flexible cognitive processing. This allowed us to clearly examine state HRV as an antecedent of cognitive performance and to do so without any potentially confounding influence of physical movement during the HRV recording.

Method

Participants

Thirty-three students (30 men, 3 women) in France, ages 18–35 years (*M* = 23.0, *SD* = 3.78), voluntarily participated in the experiment (this proportion of men to women is representative of the proportion present in the in the course section selected for the experiment). Participation was limited to individuals who did not have any cardiovascular problems, were not taking any medication, were not red–green or blue–yellow color deficient, and had not ingested caffeine, nicotine, or food at least 3 h prior to the experiment. All participants gave informed consent.

Design and Procedure

Participants were randomly assigned to one of three between-subjects experimental conditions: the red condition, the blue condition, or the gray condition. Participants were run individually by an experimenter blind to experimental condition and hypotheses. All instructions and materials were presented in French. Participants were informed that they would be taking two IQ tests commonly used to assess working memory in adults. They then took the first test; no feedback was provided. Next, participants were told that prior to the second test, physiological data would be obtained during two 3-min rest periods. The first 3-min HRV assessment then took place.

Next, participants were handed a white binder with three pages in it. The first page contained the color manipulation, which was a piece of Epson Enhanced Matte white paper containing a 18 × 12.68-cm colored rectangle with the words "Experimental Test" printed in black ink in 34 point font in the middle of the rectangle. Adobe Photoshop was used to put color on the rectangle, and the colors for the manipulation were selected using the CIELCh color model and a GretagMacBeth Eye-One Pro spectrophotometer. A trial-and-error process was used to find standard red, blue, and gray hues that were equal on lightness and chroma. The parameters for the printed colors were red LCh(49.9, 50.9, 27.0), blue LCh(49.6, 50.4, 271.0), and gray LCh(50.1, 10.4, 270.9). The experimenter instructed participants to open the binder to the first page containing the words "Experimental Test." After 2 s had elapsed, the experimenter told participants to turn the page.

The second page contained the words "Recording: Hands on Thighs" printed in black ink in the middle of a white page, to remind participants of the standardized position for the HRV assessment. The second 3-min HRV assessment then took place. After the second HRV assessment, participants were instructed to turn to the next page in the binder. This third page contained a brief questionnaire comprised of the mood and general activation items.

Following the brief questionnaire, participants took the second IQ test. At the end of the experiment, participants received a verbal funnel debriefing that probed for awareness of the purpose of the experiment (e.g., "What do you think we were trying to test?"). They were then asked to name the color that they saw on the manipulation, were told the true purpose of the experiment, and were dismissed.

Measures

Heart rate and respiratory rate. During the two electrocardiogram (ECG) assessment periods, participants were instructed to sit quietly with their hands on their thighs without speaking or moving and to breathe regularly. Participants wore a chest belt hard-wired to a digital interbeat interval (IBI) recorder (model RS 800, Polar Electro) in which the QRS-signal waveform (IBI) was sampled at the resolution of 1 ms. The IBIs (i.e., the length of time between the R peaks of consecutive QRS complexes) were calculated and checked for artifacts. Occasional ectopic beats (irregularity of the heart rhythm involving extra or skipped heart beats, i.e., extrasystole and consecutive compensatory pause) were visually identified and manually replaced with interpolated adjacent IBI values. After the ectopic-free data were detrended and resampled, a power spectral analysis was performed sequentially with a fast Fourier transform based on a nonparametric algorithm with a Welch window. A fixed linear resampling frequency of 1,024 equally spaced points per 3-min period was used. Power density in the HF (0.15–0.50 Hz) band was calculated for each 3-min spectrum by integrating the spectral power density within the frequency band.[1] An estimate of respiratory rate (RR) was derived from the central frequency of the HF component detected in an autoregressive analysis of HRV. The central frequency of HF-HRV is highly correlated with strain gauge measures of respiration (J. F. Thayer, Sollers, Ruiz-Padial, & Villa, 2002). This RR estimate enabled us to conduct analyses both without and with RR controlled, deemed important given ongoing debate on this issue in the HRV literature (see Denver, Reed, & Porges, 2007). Change (i.e., reactivity) in HF-HRV and RR between Time 1 and Time 2 was expressed in percentage form (see Duschek, Muckenthaler, Werner, & Reyes del Paso, 2009). Thus, positive values indicated an increase from Time 1 to Time 2, whereas negative values indicated a decrease from Time 1 to Time 2.

IQ performance. Two parallel forms of the memory subtest from the Wechsler Intelligence Test for adults (Wechsler, 1997, 2000) were used to assess IQ performance. These tests entail memorizing and trying to accurately repeat a series of numbers and/or letters presented orally; they are designed to assess working memory. As with the HF-HRV reactivity scores, change in IQ performance from Time 1 to Time 2 was expressed in percentage form.[2]

Self-reported mood and general activation. Mood was assessed with Greitemeyer's (2009) single-item measure ("How do you feel right now?" 1 = *very bad* to 9 = *very good*). General activation was assessed with the item "How energetic do you feel right now?" (1 = *not all energetic* to 5 = *very energetic*), which is the highest loader on the General Activation subscale of R. E. Thayer's (1986) Activation–Deactivation Adjective Check List.

Results

Preliminary Analyses and Overview

Preliminary analyses revealed no sex or age effects, so these variables were not included in the primary analyses. No participant correctly guessed the purpose of the experiment, and all participants correctly reported the color that they saw on the manipulation.

Unifactorial between-subjects (color condition: red vs. blue vs. gray) analysis of variance (ANOVA) was used to examine the effect of color on change in IQ performance, HF-HRV reactivity, RR reactivity, and the self-report variables. Fisher's least significant difference tests were used for planned comparisons. Pearson Product Moment correlation coefficients were computed to examine relations between HF-HRV reactivity and change in IQ performance. Preliminary analyses revealed no baseline (Time 1) differences in IQ performance, $F(2,30) = 0.31$, $p = .74$, $\eta_p^2 = .02$, HF-HRV, $F(2,30) = 0.30$, $p = .74$, $\eta_p^2 = .02$, and RR, $F(2,30) = 1.12$, $p = .34$, $\eta_p^2 = .07$, as a function of color condition (see Table 1).

Color Predicting Change in IQ Performance

Color condition was a significant predictor of change in IQ performance, $F(2,30) = 3.25$, $p = .05$, $\eta_p^2 = .18$. Participants in the red condition ($M = -30.64$, $SD = 10.99$) exhibited a greater decrease in performance than those in the blue condition ($M = -16.86$, $SD = 16.17$, $t = 2.13$, $p < .05$, $d = 1.00$) and the gray condition ($M = -15.89$, $SD = 17.61$, $t = 2.28$, $p < .05$, $d = 1.01$). Change in IQ performance did not differ between the blue and gray conditions ($t = 0.02$, $p = .88$, $d = 0.06$). These findings conceptually replicate prior work on red and cognitive performance (Elliot et al., 2007).

Color Predicting HF-HRV Reactivity

Analyses on HF-HRV reactivity were initially conducted without RR being controlled. Color condition was a significant predictor of HF-HRV reactivity, $F(2,30) = 6.70$, $p < .01$, $\eta_p^2 = .31$. As displayed in Figure 1, participants in the red condition ($M = -21.22$, $SD = 31.31$) exhibited decreased HF-HRV after exposure to the color, whereas those in the blue condition ($M = 5.43$, $SD = 15.61$, $t = 2.49$, $p < .05$, $d = 1.08$) and the gray condition ($M = 16.93$, $SD = 25.77$, $t = 3.57$, $p < .01$, $d = 1.33$) showed increased HF-HRV after exposure to the color. HF-HRV reactivity did not differ between the blue and gray conditions ($t = 1.08$, $p = .29$, $d = 0.54$).

Color condition was not a significant predictor of RR reactivity ($F = 2.39$, $p = .11$). Repeating the initial HF-HRV reactivity analyses after residualizing RR reactivity from the HF-HRV reactivity scores produced the same results. Color condition was a significant predictor of HF-HRV reactivity, $F(2,30) = 6.89$, $p < .01$, $\eta_p^2 = .31$. Participants in the red condition ($M = -22.09$, $SD = 27.58$) exhibited decreased HF-HRV after exposure to the color, whereas those in the blue condition ($M = 7.67$, $SD = 17.89$, $t = 2.84$, $p < .05$, $d = 1.28$) and the gray condition ($M = 14.42$, $SD = 26.96$, $t = 3.49$, $p < .01$, $d = 1.34$)

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[1] Power density in the low frequency (LF) band (0.04–0.15 Hz) was also calculated, and both HF-HRV and LF-HRV ratios were created (Buchheit & Gindre, 2006) and used in ancillary analyses. The pattern of results for the HF-HRV ratio was the same as that reported in the text for HF-HRV, and the pattern of results for the LF-HRV ratio was the reciprocal of that for HF-HRV and the HF-HRV ratio.

[2] Ancillary analyses on HF-HRV and IQ performance using analysis of covariance, rather than percentage reactivity/change scores, yield a pattern of results that was the same as that reported in the text.

Table 1. *Descriptive Statistics for the Primary Variables for Time 1 and Time 2*

	Red		Blue		Gray	
	Time 1	Time 2	Time 1	Time 2	Time 1	Time 2
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
IQ perf.	14.55 (2.54)	9.91 (1.38)	14.91 (2.63)	12.27 (2.72)	14.09 (2.17)	11.64 (1.86)
HF-HRV (nu)	40.53 (15.33)	30.05 (12.59)	36.80 (21.46)	39.27 (23.61)	34.22 (20.04)	38.17 (18.95)
RR (cpm)	10.42 (3.11)	11.44 (4.08)	12.02 (3.48)	10.82 (2.95)	10.38 (1.98)	12.12 (3.54)

Note. IQ perf. = Intelligence Quotient performance; HF-HRV = high frequency heart rate variability; RR = respiratory rate.

showed increased HF-HRV after exposure to the color. HF-HRV reactivity did not differ between the blue and gray conditions ($t = 0.65$, $p = .52$, $d = 0.30$).

Correlation between HF-HRV Reactivity and Change in IQ Performance

A significant positive relation was observed between HF-HRV reactivity and change in IQ performance ($r = .41$, $p < .05$). That is, increased HF-HRV was associated with increased performance attainment. This correlation was the same when RR reactivity was residualized from HF-HRV reactivity ($r = .44$, $p < .01$). See Table 2 for all intercorrelations among the study variables.

The Self-Report Variables

Color condition was not a significant predictor of either mood or general activation ($Fs < 1.08$, $ps > .35$). All of the results reported above remained the same when the analyses were repeated with mood and general activation controlled.

Discussion

The present research is the first to show that an "implicit affective cue" (R. S. Friedman & Förster, 2010, p. 875) influences HRV. As such, these findings link HRV to rudimentary perceptual processes involved in adaptation-relevant approach–avoidance appraisals of the environment. Red in a test context signals danger (Moller et al., 2009), so the autonomic nervous system responds with increased cardiac activity, effected via the parasympathetic nervous system, to prepare the organism to cope. This cardiac reaction is part of an emotional response (anxiety, worry; B. H. Friedman & Thayer, 1998) that itself is part of a broad "call to arms" involving cognition (e.g., perceptual vigilance) and behavioral preparation (e.g., motor readiness for fight or flight; Elliot & Thrash, 2002; J. F. Thayer & Lane, 2009). These processes operate without intention or awareness, as illustrated herein by funnel debriefing and self-report data.

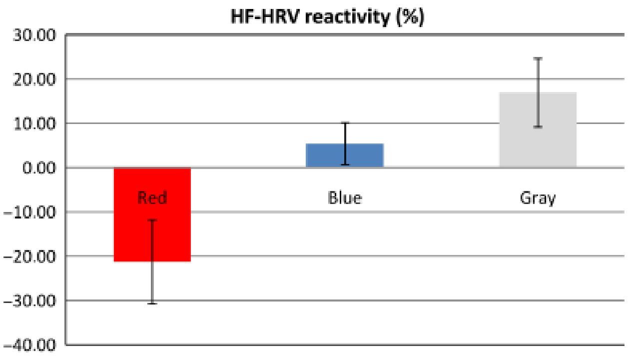

Figure 1. Mean high frequency heart rate variability (HF-HRV) reactivity as a function of color condition. Values are expressed in percentage form. Error bars represent the standard error from the mean.

Although anxiety and worry can be adaptive responses to some physical and psychological threats (Elliot, 2006), in most real-world achievement contexts they disrupt flexible cognition and lead to worse performance attainment (Cury, Da Fonseca, Zahn, & Elliot, 2008; Elliot & McGregor, 1999). In accord with this pattern, our results indicate that a state decrease in HRV is associated with a drop in IQ test performance. Although consistent with most extant research, this finding may, at first glance, seem to contradict a recent article by Duschek et al. (2009) linking reduced HRV to better cognitive performance. However, there are several noteworthy differences between the two experiments. Duschek et al. assessed HRV reactivity during task engagement (when factors other than emotion regulation contribute to autonomic functioning; see Lehrer et al., 2010), assessed cognitive performance once (yielding a score reflecting a combination of general cognitive ability and current cognitive functioning), and used a task requiring low-level cognitive processing known to be facilitated by anxiety (Seibt & Förster, 2004). In our experiment, we assessed HRV reactivity independent of task engagement, assessed change in cognitive performance, and used a task requiring high-level cognitive processing known to be undermined by anxiety (Hembree, 1988). Thus, both the Duschek et al. and our findings map nicely onto the established literature on anxiety and cognitive performance. Subsequent research would do well to use multiple tasks within a single experiment to test whether indeed the same threat stimulus evokes a decrease in HRV while simultaneously enhancing performance on a low-level task and undermining performance on

Table 2. *Intercorrelations among Study Variables*

	1.	2.	3.	4.	5.
1. IQ perf.	—				
2. HF-HRV react.	.41*	—			
3. HF-HRV react. (RR react. cont.)	.44**	.98**	—		
4. Mood	−.03	.08	.10	—	
5. General activation	.03	.16	.18	.58**	—

Note. IQ perf. = Intelligence Quotient performance; HF-HRV react. = high frequency heart rate reactivity; RR react. cont. = respiratory rate reactivity controlled.
*$p < .05$; **$p < .01$.

a high-level task. Subsequent research would also do well to examine whether the results from our research hold in achievement situations where performance across conditions increases from Time 1 to Time 2, rather than decreases as observed in our experiment.

There has been a recent influx of research on color and psychological functioning, and the present work extends this provocative literature by linking red to cardiac functioning. Color, especially red, is clearly a meaning-based as well as aesthetic stimulus, able to affect activity at multiple levels of the neuraxis. Interestingly, in a number of published HRV experiments (Gilissen, Koolstra, van IJzendoorn, Bakermans-Kranenburg, & van der Veer, 2007; Herbert, Pollatos, Flor, Enck, & Schandry, 2009; Lehrer et al., 2010; Martin et al., 2010), color, including red, has been used in experimental procedures in incidental fashion (e.g., on a fixation stimulus during baseline HRV assessment). Our findings suggest that this is problematic, as color may influence affect, cognition, and behavior in such contexts, adding unsystematic variance at minimum and perhaps even producing systematic, but undetected, effects.

Placed in the broader context of the HRV literature, our findings add support to the contention that state and trait HRV are linked to important processes and outcomes in a similar fashion. J. F. Thayer and Lane (2009) have argued that "HRV functions at both the trait and state levels as a resource" (p. 85), and the emerging empirical corpus indeed suggests that either chronic or temporary decrements in this resource is problematic for emotional experience and cognitive functioning. As such, in accord with both Polyvagal Theory (Porges, 1995, 2001) and the Neurovisceral Integration Model (J. F. Thayer & Friedman, 2002; J. F. Thayer & Lane, 2000), HRV seems to reflect the integrity of integrative functioning across the central and autonomic nervous systems in the service of goal-directed behavior.

References

Akselrod, S., Gordon, D., Ubel, F. A., Shannon, D. C., Barger, A. C., & Cohen, R. J. (1981). Power spectrum analysis of heart rate fluctuations: A quantitative probe of beat-to-beat cardiovascular control. *Science*, *213*, 220–222.

Bernstein, G. G., Bigger, J. T., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., et al. (1997). Heart rate variability: Origins, methods, and interpretive caveats. *Psychophysiology*, *34*, 623–648.

Buchheit, M., & Gindre, C. (2006). Cardiac parasympathetic regulation: Respective associations with cardiorespiratory fitness and training load. *American Journal of Physiology: Heart and Circulatory Physiology*, *291*, H451–H458.

Croizet, J., Despres, G., Gauzins, M., Huguet, P., Leyens, J., & Meot, A. (2004). Stereotype threat undermines intellectual performance by triggering a disruptive mental load. *Personality and Social Psychology Bulletin*, *30*, 721–731.

Cury, F., Da Fonseca, D., Zahn, I., & Elliot, A. J. (2008). Implicit theories and IQ test performance: A sequential mediational analysis. *Journal of Experimental Social Psychology*, *44*, 783–791.

Denver, J. W., Reed, S. R., & Porges, S. W. (2007). Methodological issues in the quantification of respiratory sinus arrhythmia. *Biological Psychology*, *74*, 286–294.

Duschek, S., Muckenthaler, M., Werner, N., & Reyes del Paso, G. A. (2009). Relationships between features of autonomic cardiovascular control and cognitive performance. *Biological Psychology*, *81*, 10–17.

Elliot, A. J. (2006). The hierachical model of approach–avoidance motivation. *Motivation and Emotion*, *30*, 111–116.

Elliot, A. J., & Maier, M. A. (2007). Color and psychological functioning. *Current Directions in Psychological Science*, *16*, 250–254.

Elliot, A. J., Maier, M. A., Binser, M. J., Friedman, R., & Pekrun, R. (2009). The effect of red on avoidance behavior. *Personality and Social Psychology Bulletin*, *35*, 365–375.

Elliot, A. J., Maier, M. A., Moller, A. C., Friedman, R., & Meinhardt, J. (2007). Color and psychological functioning: The effect of red on performance attainment. *Journal of Experimental Psychology: General*, *136*, 154–168.

Elliot, A. J., & McGregor, H. A. (1999). Test anxiety and the hierarchical model of approach and avovidance achievement motivation. *Journal of Personality and Social Psychology*, *76*, 628–644.

Elliot, A. J., & Thrash, T. M. (2002). Approach–avoidance motivation in personality: Approach and avoidance temperaments and goals. *Journal of Personality and Social Psychology*, *82*, 804–818.

Frazier, T. W., Strauss, M. E., & Steinhauer, S. R. (2004). Respiratory sinus arrhythmia as an index of emotional response in young adults. *Psychophysiology*, *41*, 75–83.

Friedman, B. H. (2007). An autonomic flexibility-neurovisceral integration model of anxiety and cardiac vagal tone. *Biological Psychology*, *74*, 185–199.

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

Friedman, R. S., & Förster, J. (2010). Implicit affective cues and attentional tuning: An integrative review. *Psychological Bulletin*, *136*, 875–893.

Gilissen, R., Koolstra, C. M., van IJzendoorn, M. H., Bakermans-Kranenburg, M. J., & van der Veer, R. (2007). Physiological reactions of preschoolers to fear-inducing clips: Effects of temperamental fearfulness and quality of the parent-child relationship. *Developmental Psychobiology*, *49*, 187–195.

Greitemeyer, T. (2009). The effect of anticipated affect on persistence and performance. *Personality and Social Psychology Bulletin*, *35*, 172–186.

Hansen, A. L., Johnsen, B. H., Sollers, J. J., Stenvik, K., & Thayer, J. F. (2004). Heart rate variability and its relation to prefrontal cognitive function: The effects of training and detraining. *European Journal of Applied Physiology*, *93*, 263–272.

Hansen, A. L., Johnsen, B. H., & Thayer, J. F. (2003). Vagal influence on working memory and attention. *International Journal of Psychophysiology*, *48*, 263–274.

Hansen, A. L., Johnsen, B. H., & Thayer, J. F. (2009). Relationship between heart rate variability and cognitive function during threat of shock. *Anxiety, Stress, and Coping*, *22*, 77–89.

Hebb, D. O. (1955). Drives and the C.N.S. (conceptual nervous system). *Psychological Review*, *62*, 243–254.

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

Herbert, B. M., Pollatos, O., Flor, H., Enck, P., & Schandry, R. (2009). Cardiac awareness anautonomic cardiac reactivity during emotional picture viewing and mental illness. *Psychophysiology*, *47*, 342–354.

Johnsen, B. H., Thayer, J. F., Laberg, J. C., Wormnes, B., Raadal, M., Skaret, E., et al. (2003). Attentional and physiological characteristics of patients with dental anxiety. *Journal of Anxiety Disorders*, *17*, 75–87.

Jorna, P. (1992). Spectral analysis of heart rate and psychological state: A review of its validity as a workload index. *Biological Psychology*, *34*, 237–257.

Kreibig, S. D. (2010). Autonomic nervous system activity in emotion: A review. *Biological Psychology*, *84*, 394–421.

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

Lehrer, P., Karavidas, M., Lu, S., Vaschillo, E., Vaschillo, B., & Cheng, A. (2010). Cardiac data increase association between self-report and both expert ratings of task load and task performance in flight simulator task: An exploratory study. *International Journal of Psychophysiology*, *76*, 80–87.

Lichtenfeld, S., Maier, M. A., Elliot, A. J., & Pekrun, R. (2009). The semantic red effect: Processing the word red undermines intellectual performance. *Journal of Experimental Social Psychology*, *45*, 1273–1276.

Lovallo, W. R. (2005). *Stress and health: Biological and psychological interactions* (2nd ed). Thousand Oaks, CA: Sage.

Luft, C. D., Takase, E., & Darby, D. (2009). Heart rate variability and cognitive function: Effects of physical effort. *Biological Psychology*, *82*, 166–191.

Maier, M. A., Elliot, A. J., & Lichtenfeld, S. (2008). Mediation of the negative effect of red on intellectual performance. *Personality and Social Psychology Bulletin*, *34*, 1530–1540.

Martin, L. A., Doster, J. A., Critelli, J. W., Lambert, P. L., Purdum, M., Powers, C., & Prazak, M. (2010). Ethnicity and Type D personality as predictors of heart rate variability. *International Journal of Psychophysiology*, *76*, 118–121.

Moller, A. C., Elliot, A. J., & Maier, M. A. (2009). Basic hue-meaning associations. *Emotion*, *9*, 898–902.

Porges, S. W. (1992). Vagal tone: A physiologic marker of stress vulnerability. *Pediatrics*, *9*, 498–504.

Porges, S. W. (1995). Orienting in a defensive world: Mammalian modifications of our evolutionary heritage: A Polyvagal Theory. *Psychophysiology*, *32*, 301–318.

Porges, S. W. (2001). The Polyvagal Theory: Phylogenetic substrates of a social nervous system. *International Journal of Psychophysiology*, *42*, 123–146.

Pryke, S. R., Andersson, S., Lawes, M. J., & Piper, S. E. (2001). Carotenoid status signaling in captive and wild red-collared widowbirds: Independent effects of badge size and color. *Behavioral Ecology*, *13*, 622–631.

Seibt, B., & Förster, J. (2004). Stereotype threat and performance: How self-stereotypes influence processing by inducing regulatory foci. *Journal of Personality and Social Psycholog*, *87*, 38–56.

Setchell, J. M., & Wickings, E. J. (2005). Dominance, status signals, and coloration in male mandrills (*Mandrillus sphinx*). *Ethology*, *111*, 25–30.

Tattersall, A. J., & Hockey, R. J. (1995). Level of operator control and changes in heart rate variability during simulated flight maintenance. *Human Factors*, *37*, 682–698.

Thayer, J. F., & Friedman, B. H. (2002). Stop that! Inhibition, sensitization, and their neurovisceral concomitants. *Scandinavian Journal of Psychology*, *43*, 123–130.

Thayer, J. F., Friedman, B. H., & Borkovec, T. D. (1996). Autonomic characteristics of generalized anxiety disorder and worry. *Biological Psychology*, *39*, 255–266.

Thayer, J. F., Hansen, A. L., Saus-Rose, E., & Johnsen, B. H. (2009). Heart rate vulnerability, prefrontal neural function, and cognitive performance: The Neurovisceral Integration perspective on self-regulation, adaptation, and health. *Annals of Behavioral Medicine*, *37*, 141–153.

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

Thayer, J. F., & Lane, R. D. (2009). Claude Bernard and the heart-brain connection: Further elaboration of a model of neurovisceral integration. *Neuroscience and Biobehavioral Reviews*, *33*, 81–88.

Thayer, J. F., Sollers, J. J., Ruiz-Padial, E., & Villa, J. (2002). Estimating respiratory frequency from autoregressive spectral analysis of heart period. *IEEE Engineering in Medicine and Biology*, *21*, 41–45.

Thayer, R. E. (1986). Activation–Deactivation Adjective Check List: Current overview and structural analysis. *Psychological Reports*, *58*, 607–614.

Wechsler, D. (1997). *Wechsler Adult Intelligence Scale* (3rd ed). San Antonio, TX: Harcourt Assessment.

Wechsler, D. (2000). *Manuel de l'Echelle d'Intelligence de Wechsler Pour Adultes* (3e édition) [*Manual for the Wechsler Adult Intelligence Scale* (3rd ed.)]. Paris, France: ECPA.

Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit formation. *Journal of Comparative and Neurological Psychology*, *18*, 459–482.

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