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The Heartbrake of Social Rejection: Heart Rate Deceleration in Response to Unexpected Peer Rejection

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Abstract

Social relationships are vitally important in human life. Social rejection in particular has been conceptualized as a potent social cue resulting in feelings of hurt. Our study investigated the psychophysiological manifestation of hurt feelings by examining the beat-by-beat heart rate response associated with the processing of social rejection. Study participants were presented with a series of unfamiliar faces and were asked to predict whether they would be liked by the other person. Following each judgment, participants were provided with feedback indicating that the person they had viewed had either accepted or rejected them. Feedback was associated with transient heart rate slowing and a return to baseline that was considerably delayed in response to unexpected social rejection. Our results reveal that the processing of unexpected social rejection is associated with a sizable response of the parasympathetic nervous system. These findings are interpreted in terms of a cardiovagal manifestation of a neural mechanism implicated in the central control of autonomic function during cognitive processes and affective regulation.

Social interaction and relationships are a hallmark of the human species. People are strongly motivated to gain social acceptance and are therefore typically highly sensitive to interpersonal rejection. Indeed, social rejection is conceptualized as a significant threat to survival (e.g., Baumeister & Leary, 1995). In addition, social rejection is implicated in the development of a wide range of psychological disorders (Deater-Deckard, 2001; Nolan, Flynn, & Garber, 2003). Laboratory studies on the phenomenological experience of social rejection predominantly investigate the emotional consequences of short-term rejection by strangers. In such studies, rejection has been shown to elicit high levels of negative emotions and distress (Buckley, Winkel, & Leary, 2004; Leary, Koch, & Hechenbleikner, 2001). Just as stressful events typically result in elevated cortisol secretion, social rejection elicits higher levels of cortisol (Blackhart, Eckel, & Tice, 2007). In addition, studies highlight the significant impact of social rejection by showing that rejection is distressing even when it results in financial gain (van Beest & Williams, 2006) or when the rejection is by a computer (Zadro, Williams, & Richardson, 2004).

Studies that explore the underlying mechanisms of social-rejection sensitivity often emphasize the benefits of avoiding rejection from an evolutionary perspective. It is likely that humans evolved a highly sensitive system in order to quickly detect signs of social rejection. More specifically, it has been proposed that by recognizing social rejection as painful, the brain is equipped with an efficient alarm system (Eisenberger & Lieberman, 2004; MacDonald & Leary, 2005). Eisenberger, Lieberman, and Williams (2003) examined the hypothesized overlap between brain mechanisms implicated in social pain and mechanisms associated with physical pain. They used functional magnetic resonance imaging in participants who were playing a virtual ball tossing game (Cyberball), in which they were excluded from social interactions. The results of this study showed that the dorsal anterior cingulate cortex (dACC), anterior insula, and right ventral prefrontal cortex (RVPFC) were more active during periods of social exclusion than during periods of social inclusion. In particular, whereas dACC changes correlated positively with self-reported distress, RVPFC changes correlated negatively with self-reported distress. This pattern of findings suggests that the RVPFC

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regulates distress felt during social exclusion by disrupting dACC activity (see also Eisenberger & Lieberman, 2004). These findings are consistent with earlier animal studies on attachment showing that separation distress recruits the brain's social pain system, a widely distributed network that includes the ACC (e.g., Panksepp, 2003).

Despite the wealth of research suggesting that social rejection produces feelings of hurt, it is not yet known how these feelings of hurt are represented in bodily responses. The goal of our study was to examine the impact of social rejection on autonomic nervous system function, by examining changes in time intervals between heartbeats. Beat-by-beat heart rate changes are under the joint control of the sympathetic nervous system and the parasympathetic nervous system. Whereas it takes the sympathetic system several seconds to increase the rate of beating of the heart, the parasympathetic system affects the heart very quickly by decreasing the rate of heartbeats. A substantial body of evidence describes how the brain acts in the regulation of the autonomic nervous system (see Cechetto & Shoemaker, 2009, for a recent review).

Several neuroimaging studies have shown that regions of the ACC, an area previously implicated in negative feelings of social rejection, are involved in cardiovagal control (e.g., Ahs, Sollers, Furmark, Fredrikson, & Thayer, 2009; Lane et al., 2009; Wong, Massé, Kimmerly, Menon, &, Shoemaker, 2007), suggesting an overlap between areas of the brain that are involved in social rejection processing and areas that are involved in the central regulation of heartbeat timing. In addition, Porro, Cettolo, Francescato, and Baraldi (2003) observed systematic relations between the activation of several ACC regions and changes in heart rate during the anticipation of pain. More recent studies have also shown that ACC activity mediates heart rate changes associated with negative affect (e.g., Urry, van Reekum, Johnstone, & Davidson, 2009). This combined evidence suggests that the dACC, and other ACC areas to which the dACC is connected, plays a key role in the regulation of a cortical-autonomic network associated with the processing of negative affect (Thayer & Brosschot, 2005; Vogt, 2005). We hypothesized that social rejection results in feelings of hurt that affect the parasympathetic system, and that social rejection is therefore accompanied by a transient slowing of heart rate.

To assess the cardiac response associated with social rejection processing, we used a modified version of a paradigm used by Somerville, Heatherton, and Kelley (2006). Several weeks before testing, participants in the current study were asked to submit a portrait photograph of themselves and were led to believe that other individuals would form impressions of them on the basis of that photograph. During the experiment, participants viewed the faces of these other individuals and were asked to predict whether the other people would like them. Participants then received acceptance or rejection feedback from these individuals, feedback that (unbeknownst to the participants) was generated by a computer. Somerville et al. observed that the ventral area of

the ACC is sensitive to social feedback (social acceptance vs. social rejection), whereas the dACC is responsive to expectancy violations.

Given the strong negative impact of social rejection, we predicted that feedback communicating social rejection would be associated with cardiac slowing. We also aimed to test whether the impact of social rejection differs according to prior expectations associated with acceptance and rejection. This context dependency of feedback effects would be consistent with studies showing that prior knowledge and person-related schemas are important in guiding social and emotional behavior (e.g., Nummenmaa, Peets, & Salmivalli, 2008). More specifically, we expected that cardiac slowing would be most pronounced in response to rejection feedback following an expectation to be liked. We also expected a weaker cardiac-slowing response to social rejection feedback following a negative expectation of social evaluation, as such feedback would be aligned with the individual's own expectations of social evaluation.

We added a nonsocial task to this experimental paradigm (Somerville et al., 2006) to determine whether the processing of social rejection heightens the cardiac response that occurs as a result of negative cognitive-performance feedback alone. The nonsocial task was identical to the social task, but differed in the type of judgments participants were required to make. Participants were asked to judge whether the person in the photograph was 21 years of age or older and were then given feedback indicating their accuracy in estimating the age of the other person. We predicted that negative feedback, or feedback not aligned with the expectations of the participant, would be associated with a transient heart rate slowing (e.g., Crone et al., 2003). However, we expected the magnitude of this cardiac response to be considerably lower than the response in the social-judgment task, assuming that the impact of social rejection is stronger than the effect of negative performance feedback. We hope that our findings can provide valuable insights into the neural mechanisms of cognitive and affective responses to social rejection.

Method
Participants

Twenty-seven undergraduate students between the ages of 18 and 25 participated in our study (18 female, 9 male; mean age = 19.9 years, *SD* = 2.22 years), in exchange for course credit or a fixed payment. All participants reported that they were healthy, had normal or corrected-to-normal vision, and had no history of neurological or psychiatric disorders. Five additional participants (4 female, 1 male; mean age = 19.8 years, *SD* = 1.72 years) were excluded from the study because of uncorrectable artifacts in their electrocardiogram (ECG) recordings, because they expressed doubts about the experiment's cover story, or because of an insufficient number of observations in the task conditions.
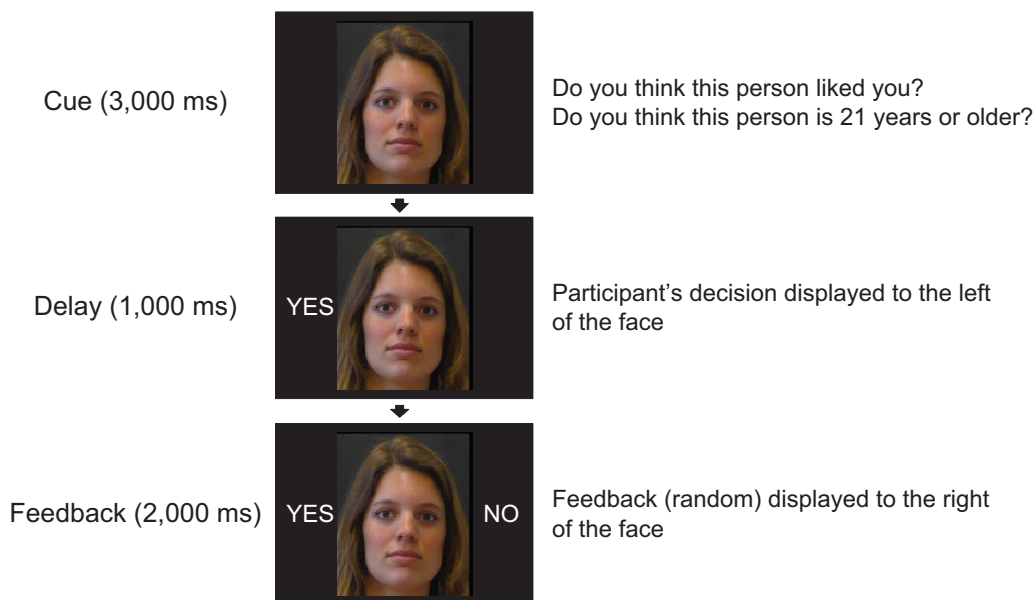
Stimulus materials and task description

Approximately 2 weeks prior to the experiment, study participants were contacted by telephone, informed that they were enrolled in a study about first impressions, and asked to send a portrait photograph of themselves to the researcher. Participants were told that their photograph would be sent to another university participating in the study, where a panel of undergraduates would be forming first impressions of them during this interim period. During the experiment, participants performed two tasks (a social-judgment task and an age-judgment task), in which they were asked to observe the neutral faces of age-matched peers. Each face (5.9 cm × 7.4 cm) was presented in color against a black background, in the center of a 17-in. computer screen (see Fig. 1). A total of 120 pictures of different faces were used, with an equal distribution of male and female faces (60 male, 60 female). Each facial stimulus was displayed once in each task. Facial stimuli were obtained by taking photographs of students between the ages of 18 and 25 at the campus of another university (mean age = 22.1, SD = 2.17 years), after the students had given their written consent.

Both the social-judgment task and the age-judgment task required participants to make judgments about the presented faces, but the tasks differed in the type of judgment required. In the social-judgment task (adopted from Somerville et al., 2006), participants were instructed to predict whether the person in the picture would accept or reject them. In each trial, the participant was required to answer the question, "Do you think this person liked you?" In the age-judgment task, participants were asked to decide whether the person in the picture was 21 years of age or older. Judgments in both tasks were followed by feedback. In the social-judgment task, feedback indicated either acceptance ("yes") or rejection ("no") by the person in the picture. In reality, the feedback in the social-judgment task was generated by a computer and not by the individuals shown on the screen. In the age-judgment task, feedback conveyed the participant's accuracy in estimating the age of the other person. This task served as a control task to examine cardiac responses to feedback outcomes that did not have a social component.

Each trial sequence (see Fig. 1) started with a 3,000-ms cue displaying a neutral face, which remained on the screen until the end of the trial. During the cue display, participants responded "yes" or "no" by pressing the "b" or "m" key of a computer keyboard, using the index or middle finger of the dominant hand. Participants were required to respond within a 3,000-ms time frame. Lack of response within this time period elicited the feedback "too slow," signaling the end of the trial. This feedback was given to participants in 0.62% of the trials in the social-judgment task and 0.74% of the trials in the age-judgment task; the percentage did not differ significantly between tasks (p > .05). Participants' choices ("yes" or "no") that were made within the time frame appeared to the left of the face, during a fixed delay of 1,000 ms. During the 2,000-ms feedback period, feedback ("yes" or "no") appeared to the right of the face. During the intertrial interval, a central fixation cross was presented on the screen. This interval varied in length, from 450 ms to 1,550 ms (1,000 ms on average).

Cue (3,000 ms)		Do you think this person liked you? Do you think this person is 21 years or older?
Delay (1,000 ms)	YES	Participant's decision displayed to the left of the face
Feedback (2,000 ms)	YES NO	Feedback (random) displayed to the right of the face

Fig. 1. Example of a trial sequence (yes/no condition) for both the social-judgment task and the age-judgment task. During the cue period, participants responded to the question, "Do you think this person liked you?" (social-judgment task) or to the question, "Do you think this person is 21 years or older?" (age-judgment task). During the following delay period, the participant's response ("yes" or "no") appeared to the left of the face. Finally, during the feedback period, feedback ("yes" or "no") appeared to the right of the face. During the intertrial interval (1,000 ms on average), a central fixation cross was shown on the screen.

Experimental design

The order of the two tasks was counterbalanced across participants. In both tasks, facial stimuli and feedback type were presented in a random order. Participants received "yes" feedback in half of the trials and "no" feedback in the other half. Both tasks included four conditions, defined by the combination of the participant's response and the feedback: yes/yes, yes/no, no/yes, and no/no. Note that the tasks differed in what constituted negative feedback. In the social-judgment task, participants received negative feedback in the yes/no and no/no conditions, with "no" communicating social rejection. In the age-judgment task, however, participants received negative feedback in the yes/no and no/yes conditions. In the yes/no condition, participants incorrectly estimated the person in the picture to be 21 years of age or older, and in the no/yes condition, participants incorrectly estimated the person in the picture to be younger than 21 years of age. Hence, the critical comparisons are between the yes/no condition of the social-judgment task and (a) the other conditions of the social-judgment task and (b) the yes/no and no/yes conditions of the age-judgment task. We expected the first comparison to establish that the cardiac response to unexpected social rejection (yes/no) differs from the cardiac response to other social feedback conditions. We expected the second comparison to reveal that the cardiac response to negative social feedback is more pronounced than the cardiac response to negative cognitive feedback.

Procedure

All participants were tested individually in a quiet laboratory with dimmed light. Participants sat in a comfortable chair approximately 75 cm from the computer monitor. Each session began with a rehearsal of the experiment's cover story: Participants were told that their photograph was sent to another university participating in the study, where the photograph was viewed by a panel of undergraduates, who rated their first impressions of each participant. Participants completed 120 trials of the social-judgment task and 120 trials of the age-judgment task. The 120 trials were separated into three blocks of 40 trials, with short breaks between blocks. Participants were familiarized with the tasks by completing one block of 10 practice trials prior to each task. At the end of the experiment, participants were debriefed about the cover story. Participants who expressed doubts about the cover story were excluded from analyses.

Data recording and analysis

During both tasks, each participant's ECG was recorded continuously using the Biopac System (BIOPAC Systems, Goleta, California) at a sample frequency of 400 Hz. ECG was recorded with three matching Ag-AgCL (silver-silver chloride) electrodes, attached via the modified lead-2 placement.

The recorded interbeat intervals (IBIs; the time between individual heart beats) were screened and corrected for artifacts by specific parameters in the program that extracted the IBIs. Seven IBIs were selected around the feedback: the IBI concurrent with the feedback (IBI 0), two IBIs preceding the feedback (IBI -2, IBI -1), and four IBIs following the feedback (IBI 1 to IBI 4). In order to obtain a sensitive index of phasic heart rate change, we referenced IBI difference scores to the second IBI preceding the feedback (IBI -2) on each trial. Preliminary analyses on IBI -2 values did not result in any differences across tasks and feedback conditions (all $ps > .10$), showing that baseline values were not sensitive to any experimental manipulation before feedback presentation. In addition, analyses on the IBI -1 difference scores failed to reveal significant differences (all $ps > .10$). Given the focus of the present study on feedback processing, IBI -1 difference scores were excluded from statistical analyses. Heart rate responses were evaluated statistically using repeated measures analyses of variance (ANOVAs) with sequential IBI differences scores (IBI 0 to IBI 4). Huyn-Feldt corrections for violations of the assumptions of sphericity were used when necessary (Vasey & Thayer, 1987). All analyses were considered significant when the p value was equal to or less than .05.

Results

Behavior

Participants made on average 56.8% "yes" judgments and 42.8% "no" judgments in the social-judgment task. One-sample t tests confirmed that on average participants made significantly more "yes" judgments and significantly fewer "no" judgments relative to a 50% baseline (both $ps < .05$). These findings indicate that participants more often predicted that they would be liked than that they would be disliked. In the age-judgment task, participants made on average 53.5% "yes" judgments and 45.8% "no" judgments. Again, one-sample t tests confirmed that on average participants made significantly more "yes" judgments and significantly fewer "no" judgments relative to a 50% baseline (both $ps < .05$). The mean numbers of trials per feedback condition are presented in Table 1 for each task separately. To examine whether there were differences in the number of trials per condition across tasks, we performed a 2 (task) × 4 (feedback condition) ANOVA. This

**Table 1.** Mean Number of Trials per Feedback Condition for the Social-Judgment and the Age-Judgment Tasks

Feedback condition	Social-judgment task	Age-judgment task
yes/yes	35.1 (6.61)	32.3 (4.53)
yes/no	33.1 (6.93)	31.9 (4.42)
no/yes	24.5 (6.87)	27.3 (4.41)
no/no	26.8 (6.84)	27.7 (4.54)

Note: Standard deviations are given in parentheses.

analysis revealed a main effect of feedback condition, $F(3, 78) = 16.54$, $p < .001$, but there was no significant difference between tasks ($p > .15$).

Heart rate

Figure 2 shows heart rate responses associated with feedback processing in the social-judgment task (Fig. 2a) and the age-judgment task (Fig. 2b). All IBIs were referenced to IBI −2. An increase in IBI difference scores indicates a slowing of heart rate. As can be seen in Figure 2, heart rate slowed in anticipation

a

Yes/Yes   Yes/No   No/Yes   No/No

b

Yes/Yes   Yes/No   No/Yes   No/No
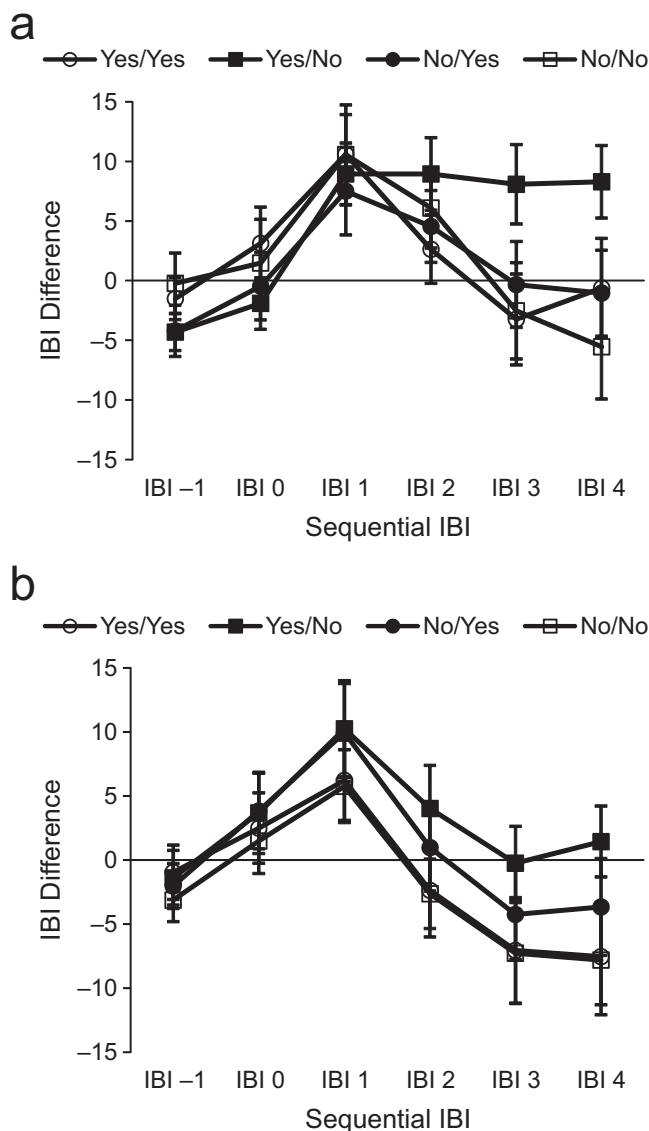
Fig. 2. Interbeat interval (IBI) response (referenced to IBI −2) associated with feedback processing in (a) the social-judgment task and (b) the age-judgment task. Results are shown for the four feedback conditions (yes/yes, yes/no, no/yes, and no/no). Feedback processing is represented for six time points: IBI −1 (prior to feedback presentation), IBI 0 (presentation of feedback), and IBI 1 to IBI 4 (following feedback presentation). An increase in the IBI difference scores indicates heart rate slowing, and a decrease indicates heart rate speeding.

of receiving feedback and showed an additional slowing following the presentation of the feedback at IBI 0. This slowing was then followed by an acceleratory recovery to baseline.

First, we predicted that unexpected negative social feedback would be associated with a delay in heart beat timing. Figure 2a shows that the IBI response to the yes/no condition differed from the cardiac response associated with the other conditions of the social-judgment task. This difference was statistically verified by performing a 2 (congruency) × 2 (feedback type) × 5 (IBI 0 to IBI 4) repeated measures ANOVA on sequential IBIs that were referenced to IBI −2. The analysis resulted in a main effect of IBI, $F(4, 104) = 6.76$, $p < .005$, and the predicted Congruency × Feedback × IBI interaction, $F(4, 104) = 3.09$, $p < .05$. No main effects for congruency and feedback type were found (both $ps > .3$). To further test our predictions concerning cardiac slowing for unexpected rejection trials (yes/no condition), we conducted paired-sample t tests on the IBIs following the presentation of the feedback (i.e., IBI 1 to IBI 4). These comparisons showed that the IBI differences scores were significantly greater for the yes/no condition than for all other feedback conditions at IBI 3—no/no: $t(26) = 2.68$, $p < .05$; no/yes: $t(26) = 2.35$, $p < .05$; and yes/yes: $t(26) = −3.4$, $p < .005$—as well as IBI 4—no/no: $t(26) = 3.08$, $p < .01$; no/yes: $t(26) = 2.28$, $p < .05$; and yes/yes: $t(26) = −2.52$, $p < .05$.

Second, we predicted that cardiac slowing in response to negative social feedback would be more pronounced than cardiac slowing in response to negative cognitive feedback. This prediction was tested by comparing the IBI response in the yes/no condition of the social-judgment task with the IBI response in the yes/no and no/yes conditions of the age-judgment task. As predicted, the IBI response to unexpected negative social feedback was greater than the response obtained in the age-judgment task for the yes/no condition, $F(4, 104) = 6.14$, $p = .001$, and the no/yes condition, $F(4, 104) = 11.41$, $p < .001$. Thus, as anticipated, the additional transient cardiac slowing at IBI 3 and IBI 4 was specific to unexpected social rejection.

Discussion

In this study, we aimed to examine the cardiac concomitants of the processing of social rejection. Participants performed two tasks with the same overall design: a social-judgment task and an age-judgment task, which served as a control. Participants viewed a series of unfamiliar faces and were asked to predict whether each person they had seen would like them or to estimate if each person they had seen was 21 years of age or older. Each judgment was followed by feedback indicating acceptance or rejection by the other person or accuracy in estimating the age of the other person. We predicted that the processing of feedback communicating social rejection would result in feelings of hurt, and would therefore be accompanied by a transient slowing of heart rate, which would be most pronounced for rejection following a positive expectation of social evaluation. In addition, we hypothesized that this response would be larger

than the cardiac response to negative cognitive feedback in the age-judgment task. Our results supported these predictions.

The percentages of positive judgments and negative judgments differed somewhat from 50% in both tasks, but it is important to note that these percentages did not differ across tasks. Both tasks yielded the typical heart rate pattern associated with feedback processing (e.g., Crone et al., 2003; van der Veen, van der Molen, Crone, & Jennings, 2004), which consists of a transient heart rate slowing to the feedback stimulus. Heart rate slowing reached its maximum during the IBI following feedback onset (IBI 1), which is consistent with other research findings in this field indicating that maximum heart rate slowing occurs during the IBI following the IBI of feedback occurrence (e.g., Crone et al., 2003). The transient slowing of heart rate in response to the feedback stimulus is usually interpreted in terms of a vagal response associated with the cognitive elaboration of the information provided by the stimulus (e.g., van der Molen, Somsen, Jennings, Nieuwboer, & Orlebeke, 1987).

The transient slowing of heart rate associated with feedback processing was followed by an acceleratory recovery to baseline. Research has established that this recovery is delayed when the feedback stimulus conveys negative information, that is, when the stimulus provides negative performance feedback (e.g., Hajcak, McDonald, & Simons, 2003), signals punishment (e.g., Luman, Oosterlaan, Knol, & Sergeant, 2008), or signals a violation of expectations based on previous task experience (e.g., Somsen, van der Molen, Jennings, & van Beek, 2000). Recovery is also delayed following unpleasant affective stimuli (e.g., Bradley, 2009). Our findings add to this literature by showing that individuals exhibit a pronounced heart rate slowing (in effect, a "heartbrake") in response to rejection feedback when expecting a positive social evaluation. This finding suggests that social rejection literally results in bodily responses reflecting social hurt (Eisenberger et al., 2003).

We found that the cardiac response to unexpected social rejection was considerably larger than heart rate changes associated with expected social rejection. This result confirms the hypothesis on the context dependency of effects of social rejection. This finding may also suggest that negative feelings associated with being socially rejected are reduced substantially when negative peer evaluation is anticipated. Note, however, that no self-report ratings of distress were administered in our study. In future studies, it will be important to collect self-report ratings to better understand the affective responses elicited by social feedback. It is also important to note that the cardiac response we observed for unexpected social rejection was larger than the heart rate change observed for the other conditions in which feedback was not aligned with the expectations of the participant (i.e., the no/yes condition in the social-judgment task and the yes/no or no/yes conditions in the age-judgment task). This result indicates that the impact of social rejection is stronger than the effect of expectancy violation per se. Taken together, the pattern of results that emerged

from our study shows that cardiac slowing was most pronounced for unexpected social rejection.

Thus, feelings of hurt associated with unexpected social rejection result not only in central brain responses that are implicated in physical pain processing (Eisenberger et al., 2003), but also in autonomic feelings of hurt, which are reflected in changes in heart rate. This pattern of results is consistent with recent findings suggesting a link between negative affect and the parasympathetic nervous system. For example, Heilman et al. (2008) studied the psychophysiological profiles of young children in response to two different challenges—a physical challenge (i.e., bicycle pedaling) and a social challenge (i.e., the child stayed in a room with an experimenter while his or her parents exited the room). The experimenters found that heart rate increased during pedaling, which was expected, but also that heart rate decreased in response to the social challenge. From an evolutionary viewpoint, these findings support the strong motivational importance of social belonging. That is, humans are likely to have evolved a highly sensitive system to quickly process signals of social threat. Indeed, the ability of the vagus nerve to assert parasympathetic control is believed to reflect a self-regulatory process that promotes a healthy style of adaptive and flexible behavior (Thayer & Brosschot, 2005; Thayer & Lane, 2009). Cardiac deceleration has specifically been associated with enhanced sensory intake and active engagement with the environment (e.g., Bradley, 2009).

At the neural level, the dACC has been linked to both pain distress and discrepancy detection (Eisenberger et al., 2003). As a result, Eisenberger and Lieberman (2004) conceptualized the dACC as a neural alarm system in which these two functions act as complementary processes. Our findings on the context dependency of the effects of social rejection could further support this alarm-system hypothesis, as they show an interplay between expectancy violation and distress: Unexpected rejection (but not expected rejection) elicited a strong pattern of cardiac slowing. Therefore, our results suggest that both expectancy violation and distress play an important role in triggering the alarm system proposed by Eisenberger and Lieberman. It is possible that unexpected social rejection triggers the dACC alarm system by raising the alert that there is a discrepancy between an individual's expected state of social belonging and his or her actual state of belonging.

Our findings are also consistent with those of a study by Ploghaus, Becerra, Borras, and Borsook (2003), which showed a mediating role of expectations on the affective consequences of physical pain. More specifically, this study demonstrated a functional dissociation in the neural pathways involved in physical pain processing, such that expected pain activated the rostral ACC, and unexpected pain activated the dACC (Eisenberger & Lieberman, 2004). The results of our study extend these findings to the social domain, as they show a difference between the psychophysiological manifestation of unexpected social rejection and that of expected social rejection.

From a broader perspective, the current findings are also consistent with the concept of a central autonomic network, which has been recognized by investigators working in diverse areas of research (e.g., Benarroch, 1993; Saper, 2002). This network consists of both prefrontal and midbrain structures and is characterized by reciprocal interconnections. The output of the central autonomic network is directly linked to beat-by-beat heart rate changes, and sensory information from the heart is fed back to the network to allow for central autonomic integration. Indeed, studies have demonstrated correlations between heart rate changes and brain activity in areas of this network (e.g., Critchley et al., 2003; Gianaros, Van der Veen, & Jennings, 2004; Napadow et al., 2008). Our findings together with these studies support the hypothesis that cortical and midbrain areas involved in autonomic control are also implicated in cognitive processes and affective regulation (Thayer & Brosschot, 2005). Within this context, cardiac slowing associated with unexpected social rejection can be interpreted as a cardiovagal manifestation of the central autonomic network facilitating the processing of relevant social information (Porges, 2003). It would be of considerable interest to examine the cardiovagal response to social rejection in individuals who are hypersensitive to social exclusion.

References

Ahs, F., Sollers, J.J., Furmark, T., Fredrikson, M., & Thayer, J.F. (2009). High-frequency heart rate variability and cortico-striatal activity in men and women with social phobia. *NeuroImage*, *47*, 815–820.

Baumeister, R.F., & Leary, M.R. (1995). The need to belong: Desire for interpersonal attachments as a fundamental human motivation. *Psychological Bulletin*, *117*, 497–529.

Benarroch, E.E. (1993). The central autonomic network: Functional organization, dysfunction, and perspective. *Mayo Clinic Proceedings*, *68*, 988–1001.

Blackhart, G.C., Eckel, L.A., & Tice, D.M. (2007). Salivary cortisol in response to acute social rejection and acceptance by peers. *Biological Psychology*, *75*, 267–276.

Bradley, M.M. (2009). Natural selective attention: Orienting and emotion. *Psychophysiology*, *46*, 1–11.

Buckley, K.E., Winkel, R.E., & Leary, M.R. (2004). Reactions to acceptance and rejection: Effects of level and sequence of relational evaluation. *Journal of Experimental Social Psychology*, *40*, 14–28.

Cechetto, D.F., & Shoemaker, J.K. (2009). Functional neuroanatomy of autonomic regulation. *NeuroImage*, *47*, 795–803.

Critchley, H.D., Christopher, J.M., Josephs, O., O'Doherty, J., Zanini, S., Dewar, B., et al. (2003). Human cingulate cortex and autonomic control: Converging neuroimaging and clinical evidence. *Brain*, *126*, 2139–2152.

Crone, E.A., van der Veen, F.M., van der Molen, M.W., Somsen, R.J.M., van Beek, B., & Jennings, J.R. (2003). Cardiac concomitants of feedback processing. *Biological Psychology*, *64*, 143–156.

Deater-Deckard, K. (2001). Annotation: Recent research examining the role of peer relationships in the development of psychopathology. *Journal of Child Psychology and Psychiatry*, *42*, 565–579.

Eisenberger, N.I., & Lieberman, M.D. (2004). Why rejection hurts: A common neural alarm system for physical and social pain. *Trends in Cognitive Sciences*, *8*, 294–300.

Eisenberger, N.I., Lieberman, M.D., & Williams, K.D. (2003). Does rejection hurt? An fMRI study of social exclusion. *Science*, *302*, 290–292.

Gianaros, P.J., Van der Veen, F.M., & Jennings, J.R. (2004). Regional cerebral blood flow correlates with heart period and high-frequency heart period variability during working-memory tasks: Implications for the cortical and subcortical regulation of cardiac autonomic activity. *Psychophysiology*, *41*, 521–530.

Hajcak, G., McDonald, N., & Simons, R.F. (2003). To err is automatic: Error-related brain potentials, ANS activity, and post-error compensatory behavior. *Psychophysiology*, *40*, 895–903.

Heilman, K.J., Bal, E., Bazhenova, O.W., Sorokin, Y., Perlman, S.B., Hanley, M.C., et al. (2008). Physiological responses to social and physical challenges in children: Quantifying mechanisms supporting social engagement and mobilization behaviors. *Developmental Psychobiology*, *50*, 171–182.

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

Leary, M.R., Koch, E.J., & Hechenbleikner, N.R. (2001). Emotional responses to interpersonal rejection. In M. Leary (Ed.), *Interpersonal rejection* (pp. 145–166). New York: Oxford University Press.

Luman, M., Oosterlaan, J., Knol, D.L., & Sergeant, J.A. (2008). Decision-making in ADHD: Sensitive to frequency but blind to the magnitude of penalty? *Journal of Child Psychology and Psychiatry*, *49*, 712–722.

MacDonald, G., & Leary, M.R. (2005). Why does social exclusion hurt? The relationship between social and physical pain. *Psychological Bulletin*, *131*, 202–223.

Napadow, V., Dhond, R., Conti, G., Makris, N., Brown, E.N., & Barbieri, R. (2008). Brain correlates of autonomic modulation: Combining heart rate variability with fMRI. *NeuroImage*, *42*, 169–177.

Nolan, S.A., Flynn, C., & Garber, J. (2003). Prospective relations between rejection and depression in young adolescents. *Journal of Personality and Social Psychology*, *85*, 745–755.

Nummenmaa, L., Peets, K., & Salmivalli, C. (2008). Automatic activation of adolescents' peer-relational schemas: Evidence from priming with facial identity. *Child Development*, *79*, 1659–1675.

Panksepp, J. (2003). Feeling the pain of social loss. *Science*, *302*, 237–239.

Ploghaus, A., Becerra, L., Borras, C., & Borsook, D. (2003). Neural circuitry underlying pain modulation: Expectation, hypnosis, placebo. *Trends in Cognitive Sciences*, *7*, 197–200.

Porges, S.W. (2003). Social engagement and attachment. A phylogenetic perspective. *Annals of the New York Academy of Sciences*, *1008*, 31–47.

Porro, C.A., Cettolo, C., Francescato, M.P., & Baraldi, P. (2009). Functional activity mapping of the mesial hemispheric wall during anticipation of pain. *NeuroImage*, *19*, 1738–1747.

Saper, C.B. (2002). The central autonomic nervous system: Conscious visceral perception and autonomic pattern generation. *Annual Review of Neuroscience*, *25*, 433–469.

Somerville, L.H., Heatherton, T.F., & Kelley, W.M. (2006). Anterior cingulate cortex responds differentially to expectancy violation and social rejection. *Nature Neuroscience*, *9*, 1007–1008.

Somsen, R.J.M., van der Molen, M.W., Jennings, J.R., & van Beek, B. (2000). Wisconsin Card Sorting in adolescents: Analysis of performance, response times and heart rate. *Acta Psychologica*, *104*, 227–257.

Thayer, J.F., & Brosschot, J.F. (2005). Psychosomatics and psychopathology: Looking up and down from the brain. *Psychoneuroendocrinology*, *30*, 1050–1058.

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.

Urry, H.L., van Reekum, C.M., Johnstone, T., & Davidson, R.J. (2009). Individual differences in some (but not all) medial prefrontal regions reflect cognitive demand while regulating unpleasant emotion. *NeuroImage*, *47*, 852–863.

van Beest, I., & Williams, K.D. (2006). When inclusion costs and ostracism pays, ostracism still hurts. *Journal of Personality and Social Psychology*, *91*, 918–928.

van der Molen, M.W., Somsen, R.J., Jennings, J.R., Nieuwboer, J.F., & Orlebeke, A. (1987). A psychophysiological investigation of cognitive energetic relations in human information processing: A heart rate / additive factors approach. *Acta Psychologica*, *66*, 251–289.

van der Veen, F.M., van der Molen, M.W., Crone, E.A., & Jennings, J.R. (2004). Phasic heart rate responses to performance feedback in a time production task: Effects of information versus valence. *Biological Psychology*, *65*, 147–161.

Vasey, M.W., & Thayer, J.F. (1987). The continuing problem of false positives in repeated measures ANOVA in psychophysiology: A multivariate solution. *Psychophysiology*, *24*, 479–486.

Vogt, B.A. (2005). Pain and emotion interactions in subregions of the cingulate gyrus. *Nature Reviews Neuroscience*, *6*, 533–544.

Wong, S.W., Massé, N., Kimmerly, D.S., Menon, R.S., & Shoemaker, J.K. (2007). Ventral medial prefrontal cortex and cardiovagal control in conscious humans. *NeuroImage*, *35*, 698–708.

Zadro, L., Williams, K.D., & Richardson, R. (2004). How low can you go? Ostracism by a computer is sufficient to lower self-reported levels of belonging, control, self-esteem, and meaningful existence. *Journal of Experimental Social Psychology*, *40*, 560–567.