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From the heart to the mind's eye: Cardiac vagal tone is related to visual perception of fearful faces at high spatial frequency☆

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ABSTRACT

The neurovisceral integration model (Thayer and Lane, 2000) proposes that vagally mediated heart rate variability (HRV)—an index of cardiac vagal tone—is associated with autonomic flexibility and emotional self-regulation. Two experiments examined the relationship between vagally mediated HRV and visual perception of affectively significant stimuli at different spatial frequencies. In Experiment 1, HRV was positively correlated with superior performance discriminating the *emotion* of affectively significant (i.e., fearful) faces at high spatial frequency (HSF). In Experiment 2, processing goals moderated the relationship between HRV and successful discrimination of HSF fearful faces. In contrast to Experiment 1, discriminating the *expressiveness* of HSF fearful faces was not correlated with HRV. The current research suggests that HRV is positively associated with superior visual discrimination of affectively significant stimuli at high spatial frequency, and this relationship may be sensitive to the top-down influence of different processing goals.

1. Introduction

Human facial expressions provide important social and biological information. According to Darwin (1872), facial expressions evolved because they facilitated rapid nonverbal communication. The ability to accurately discriminate between different expressions is critical for successful navigation of the social world. Indeed, research suggests that people can efficiently detect and discriminate emotional expressions and use this information to guide their behavior (Adolphs, 2001; Ekman and Friesen, 1971; Marsh et al., 2005; Susskind et al., 2008). The current research examines whether cardiac vagal tone, a mechanism by which cortical activity modulates cardiovascular function, is associated with the visual discrimination of affectively significant facial expressions at different spatial frequencies.

1.1. The neurovisceral integration model and heart rate variability

The vagus nerve provides inhibitory inputs to the heart via the parasympathetic nervous system to regulate metabolic responses to the environment (Thayer and Lane, 2000; see also Porges, 2003). Neural circuits link the heart with cortical and subcortical brain structures via the vagus nerve (see also Benarroch, 1993; Berntson et al., 1997; Levy, 1971) and robust regulation of the heart via the vagus nerve (i.e., high vagal tone) is associated with a nervous system that responds quickly and flexibly to environmental demands (Ellis and Thayer, 2010; Thayer and Lane, 2000; Thayer et al., 2009). Therefore, cardiac vagal tone is associated with more adaptive patterns of emotional responding and self-regulation (see Friedman, 2007; Porges, 1991; Thayer and Friedman, 2004; Thayer et al., 2009). Heart rate variability (HRV), which refers to the differences in beat-to-beat alterations in heart rate, provides an index of cardiac vagal tone (Berntson et al., 1997; Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996; Thayer and Lane, 2000). High vagally-mediated HRV is associated with highly integrated cortical-subcortical circuits that result in an exertion of good cognitive, emotional, and physiological self-regulation (Thayer et al., 2009). In contrast, low HRV is associated with poor functioning of regulatory systems resulting from the lack of prefrontal regulation over subcortical activity (Thayer et al., 2009).

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A number of studies have confirmed that individual differences in HRV are closely linked with executive function in the prefrontal cortex and emotional processing in the amygdala (Thayer et al., 2009). For example, people with high HRV were faster and more accurate in an attentional task and a two-back working memory test (Hansen et al., 2003). Using computational neural network models to simulate emotional processing, Thayer and Siegle (2002) showed that reduced HRV was associated with overactive amygdala activity and reduced PFC activity. These studies suggest that HRV is associated with cognitive and emotional responses that are situationally adaptive and flexible (Thayer et al., 2009). The goal of the current research is to examine whether HRV is associated with enhanced visual discrimination of affectively significant stimuli.

1.2. The role of spatial frequency in face perception

A number of neuroimaging studies have investigated the neural mechanisms associated with perceiving facial emotions at different spatial frequencies (Vuilleumier et al., 2003; Vuilleumier and Pourtois, 2007; Winston et al., 2003). Spatial frequency is described by the energy distribution in the scale specified as the number of cycles per degree of visual angle and/or the number of cycles per image (Morrison and Schyns, 2001; Parker et al., 1996). Broad spatial frequency (BSF) images contain all spatial frequency ranges and may be filtered to contain either high spatial frequency or low spatial frequency (Holmes et al., 2005; Vuilleumier et al., 2003). High spatial frequency (HSF) information—above 24 cycles per image—is conveyed via the *parvocellular* pathway, which mediates perception of color and contrast (Merigan and Maunsell, 1993; Vuilleumier et al., 2003). Due to thin nerve fibers, the parvocellular pathway transfers information slowly, but with high resolution (Merigan and Maunsell, 1993), and faces at high spatial frequency exhibit fine edges (Goffaux et al., 2005; Goffaux and Rossion, 2006; see Fig. 1). HSF fearful faces elicit greater activity in ventral visual cortical areas, including the bilateral fusiform and the inferior temporal-occipital cortex (Vuilleumier et al., 2003). Furthermore, Winston and colleagues (2003) used hybrid stimuli, which were constructed by overlapping a male or female face exhibiting a particular emotional expression (e.g., fearful) presented at LSF with a face of the other gender exhibiting a different facial expression (e.g., neutral) at HSF. They found that HSF fearful faces elicited greater responses in the posterior cingulate, the motor cortex, the medial prefrontal cortex and the lateral orbitofrontal cortex.

Low spatial frequency (LSF) information—below eight cycles per image—is conveyed via the *magnocellular* pathway which rapidly mediates perception of depth, motion, and low contrast black-and-white information (Livingstone and Hubel, 1988; Merigan and Maunsell, 1993; Nieuwenhuis et al., 2008; Vuilleumier et al., 2003). In addition, the phylogenetically old *retinotectal* pathway, which routes information from the retina through the superior colliculus and pulvinar nucleus of the thalamus, primarily carries low spatial frequency information to the amygdala (Livingstone and Hubel, 1988; Merigan and Maunsell, 1993; Nieuwenhuis et al., 2008; Vuilleumier et al., 2003). As a result, greater amygdala activity was elicited by blurred and coarse LSF fearful faces compared to LSF neutral faces, but the amygdala was unresponsive to HSF fearful faces (Vuilleumier et al., 2003).

A previous study that employed statistical image analysis suggested that discriminating the emotion of HSF faces was difficult, whereas it was easy to discriminate the emotion of LSF faces (Mermillod et al., 2008). When statistical properties of fearful and neutral faces at different spatial frequency information were analyzed, the statistical distributions of HSF fearful and neutral faces overlapped completely so that it was difficult for observers to discriminate emotion using HSF information (Mermillod et al., 2008). In contrast, statistical properties of LSF information allowed observers to effectively discriminate fearful and neutral expressions. Thus, the authors suggested that using LSF information would be optimal for emotion discrimination tasks (Mermillod et al., 2008).

1.3. Overview

In two experiments, we investigated the relationship between vagally mediated HRV—a proposed marker of cognitive and emotional self-regulation—and the visual perception of affectively significant stimuli at high, low and unfiltered broad spatial frequency under different processing goals. In Experiment 1, we asked participants to discriminate the *emotion* (fearful versus neutral) of faces. As discussed above, discriminating emotion of HSF faces is thought to be a challenging task (Mermillod et al., 2008). In particular, the processing of HSF fearful faces is associated with greater prefrontal activity (Vuilleumier et al., 2003; Winston et al., 2003). Given the link between HRV and prefrontal cortical control, we hypothesize that individual differences in HRV will be positively correlated with higher accuracy during the discrimination of fearful faces at HSF. That is, high HRV should allow for superior executive function (e.g., focused attention) and therefore be associated with higher accuracy during the discrimination of HSF fearful faces. On the other hand, subcortical structures, such as the amygdala, are implicated in processing LSF information. Therefore, there may be less of a need to employ executive control when engaging in emotional discrimination of LSF faces (Mermillod et al., 2008; Pessoa, 2005; Vuilleumier et al., 2003). As a result, the relationship between HRV and discriminating emotion at LSF may be weaker. We also expected that HRV would not be associated with performance on discriminating BSF faces. Discriminating BSF faces is an easy task that may require less executive control. In fact, only those with severe psychiatric disorders, such as schizophrenia, show difficulty discriminating the emotion of BSF faces (Couture et al., 2006; Turetsky et al., 2007). We did not expect that level of behavioral impairment in a normal population.

In Experiment 2, we examined whether the relationship between HRV and the discrimination of HSF fearful faces could be attenuated by a different processing goal (i.e., *expressiveness* judgments). Previous research has suggested that processing goals play an important role in determining which spatial frequency information is utilized in face recognition (Goffaux et al., 2005; Schyns and Oliva, 1999). When participants were asked to discriminate the *emotion* of hybrid face stimuli (i.e., happy, neutral, and angry), they primarily utilized LSF information. In contrast, when participants were asked to discriminate whether the stimuli were *expressive* or *not*, they utilized HSF information. Thus, discriminating expressiveness seems to be easier with HSF information and may require less executive function (Schyns and Oliva, 1999). As a result, there should be no relationship between HRV and HSF fearful faces in the expressiveness task. Furthermore, by directly comparing the results of the emotion discrimination task in Experiment 1 with the results of the expressiveness task in Experiment 2, we sought to provide evidence of top-down modulation. This would be indicated by a significant interaction between HRV (continuous) and task instructions (emotion discrimination, expressiveness) among the HSF fearful faces. On the other hand, detecting expressiveness using LSF information alone would be difficult and require prefrontal control. Therefore, we expected that there would be a significant relationship between HRV and LSF fearful faces.

2. Experiment 1

In Experiment 1, we investigated the relationship between HRV and the visual perception of affectively significant stimuli at

Fig. 1. Example stimuli: normal broad spatial frequency (BSF) fearful and neutral faces (left column), high spatial frequency (HSF) faces (middle column), low spatial frequency (LSF) faces (right column).

different levels of spatial frequency. To study this relationship, we had participants perform an emotion discrimination task in which they were instructed to determine whether a face was fearful or neutral.

2.1. Methods

2.1.1. Participants

Forty-six undergraduate students successfully completed the study for partial course credit.[1] All participants were asked to refrain from alcohol, drug use, smoking, and caffeinated beverages for 4 h prior to participation (Hansen et al., 2003). All participants had normal or corrected to normal vision (20/20 visual acuity). People with a history of vision disorders or dysfunctions, neurological or psychiatric disorders, cardiovascular disorders, or medical conditions such as diabetes were excluded from this experiment. We excluded data from two participants who had more than 15% of missing trials due to errors and outliers, yielding forty-four participants (25 women; mean age = 20).

2.1.2. Stimuli

We selected 132 faces (66 with fearful expressions and 66 with neutral facial expressions; 33 women and 33 men with each expression) from the Karolinska Directed Emotional Faces set (KDEF; Lundqvist et al., 1998), the NimStim Face Stimulus Set (MacArthur Foundation Research Network on Early Experience and Brain Development), the Cohn–Kanade AU coded Facial Expression Database (Kanade et al., 2000) and Pictures of Facial Affect (Ekman and Friesen, 1976). We used 120 faces (60 fearful and 60 neutral) for experimental trials and 12 faces for practice trials. All faces were converted to gray-scale. Contrast and brightness were adjusted to maintain constancy across different face sets. As seen in Fig. 1, each face was enclosed in a circular frame using Adobe PhotoShop CS3 software (Adobe System, San Jose, CA) to exclude non-facial features (e.g., hair). In order to produce the HSF and LSF stimuli, the unfiltered (i.e., broad spatial frequency or BSF) pictures were filtered through a high-pass cut off of >24 cycles/image for the HSF stimuli and a low-pass cut off of < 6 cycles/image for the LSF stimuli. Average gray-scale values for the BSF, HSF and LSF stimuli were 166, 168, and 158, respectively, and for the neutral and fearful face categories average gray-scale values were 164 and 168, respectively, on a 256 gray-level scale. These average gray-scale values did not significantly differ across spatial frequency, $F(2, 357) = 2.02$, $p = .13$, $\eta_p^2 = .01$, or emotional expression, $F(1, 358) = 1.\ 10$, $p = .37$, $\eta_p^2 = .002$. Each stimulus measured 6° horizontally and 6° vertically against a light gray background at a viewing distance of 160 cm and was displayed on a 42 in. high definition plasma television monitor with a resolution of 1024 by 768 pixels.

2.1.3. Procedure

All participants were tested individually in a dimly-lit room. They were brought to the lab and surface electrodes were attached to obtain electrocardiographic data. After placement of electrodes, resting HRV was recorded for 5 min.

Participants then performed the emotion discrimination task. Faces were presented in three separate blocks of different spatial frequencies (BSF, HSF, LSF) and blocks were presented in counterbalanced order. Participants were told that they would be presented with a series of pictures of unfamiliar faces, and their task was to identify the emotion of each face by pressing the "1" key for fearful and the "2" key for neutral on a number pad with their dominant hand. In each block, participants were presented with 12 practice trials, followed by 120 experimental trials of fearful and neutral faces in random order. After each block, participants were allowed a short break. Each face was randomly presented three times at different spatial frequency ranges. Each trial began with a fixation point for 500 ms, followed by the display with an image for 200 ms. The interstimulus interval was 1800 ms (see Fig. 2).

[1] The behavioral and cardiovascular data from three participants were lost due to a computer error.

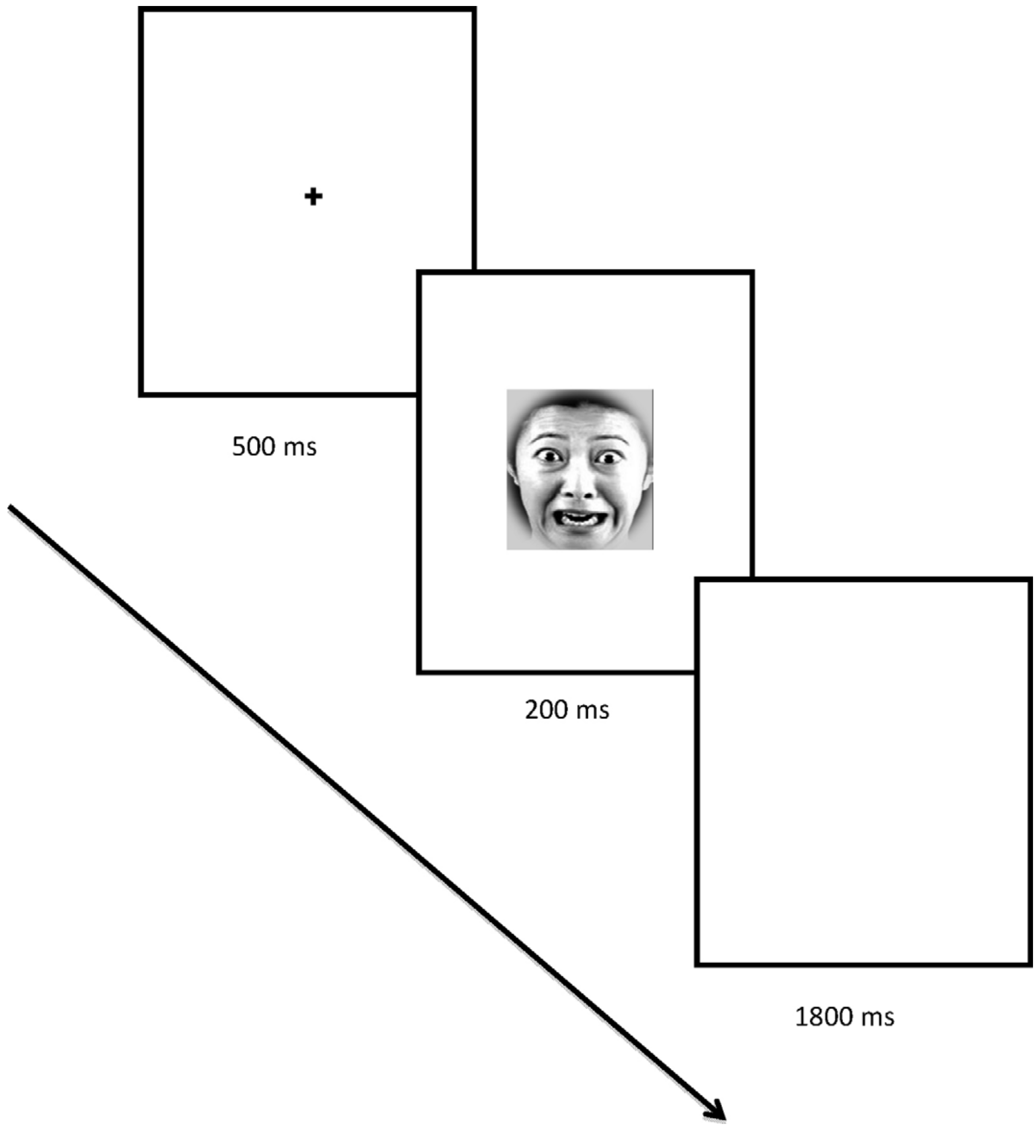

Fig. 2. Example of experimental sequence: the fixation cross was presented for 500 ms and followed by the display with an image for 200 ms. The interstimulus interval was 1800 ms. Stimuli are not drawn to scale.

Participants were instructed to respond as quickly and accurately as possible. Participants received a “No response” feedback when they failed to respond within 3000 ms. Participants did not receive feedback on whether their responses were correct or not. After the task, participants went through a 5-min recovery period.

2.1.4. Physiological measurements

We recorded electrocardiographic activity via a standard 3-electrode (lead II) setup: the negative electrode below the left collar bone, the positive electrode below the right rib cage, and the ground electrode below the left rib cage. The ECG signals, which were sampled at 1000 Hz (Task Force, 1996), passed through Mindware Technology’s BioNex 50-3711-02 two-slot mainframe to an Optiplex GX620 personal computer (Pentium D, 2.80 GHz, 2.00 GB RAM) running Mindware Technology’s BioLab 1.11 software which received digital triggers (100 ms pulses) via a parallel port connection with a second Optiplex GX620 running E-Prime 1.1.4.1 (Psychology Software Tools, Inc.). The ECG signals were inspected offline using Mindware Technology’s HRV 2.51 software with which the ECG trace (plotted in mV against time) was carefully re-examined. Successive R spikes (identified by an automatic beat detection algorithm) were visually inspected and any irregularities were edited. Successive IBIs (in ms) within the baseline period were written in a single text file and analyzed using the Kubios HRV analysis package 2.0 (http://basmig.uku.fk/biosignal) through which time and frequency domain indices of the heart period power spectrum were computed. Time domain indices include estimates of root mean square successive difference in milliseconds (rMSSD) and heart rate (HR) in beats per minute. For spectral analyses, we used autoregressive estimates following the Task Force of the European Society of Cardiology and the North American Society of Pacing Electrophysiology (1996) guidelines. rMSSD and the frequency domain measure of high frequency HRV power (HFP) are regarded as the primary indices of the cardiac vagal tone. rMSSD and high frequency HRV power were significantly correlated, $r(44) = .80$, $p < .01$. We used high frequency power as the primary index of the cardiac vagal tone in this study and spectral estimates of high frequency power (in milliseconds squared per hertz) were transformed logarithmically (base 10) to normalize the distribution (Ruiz-Padial et al., 2003).

2.1.5. Analyses

Reaction times of less than 150 ms, more than 1500 ms, or more than 2 standard deviations above the mean were considered

Table 1
Means and standard deviations of percentage of response accuracy, and reaction times (in milliseconds), as a function of types of spatial frequency and emotion in the emotion discrimination task (Experiment 1).

			Mean	SD
BSF	Fearful	Accuracy	96.8	3.2
		RTs	676.6	81.0
	Neutral	Accuracy	97.0	2.5
		RTs	686.5	83.1
HSF	Fearful	Accuracy	90.1	8.0
		RTs	723.7	75.9
	Neutral	Accuracy	92.1	5.5
		RTs	723.1	80.3
LSF	Fearful	Accuracy	90.7	4.8
		RTs	690.0	84.7
	Neutral	Accuracy	94.3	5.7
		RTs	705.2	88.5

outliers and were excluded (2% of trials; Ratcliff, 1993). All analyses on RTs exclude outliers *and* incorrect trials (Ratcliff, 1993).

To assess whether individual differences in HRV were associated with successful task performance, we created separate dummy-coded variables for facial emotion (fear = 1, neutral = 0), and low (LSF = 1, BSF = 0, HSF = 0) and high (LSF = 0, BSF = 0, HSF = 1) spatial frequency, using BSF as a reference group. We also mean-centered HRV and computed interaction terms between these variables (Aiken and West, 1991). We conducted a facial emotion (neutral, fear) × low spatial frequency (low, other) × high spatial frequency (high, other) × HRV (continuous) multiple regression analysis on response accuracy (see Cohen and Cohen, 1983; Gully, 1994). Repeated measures multiple regression adapts procedures outlined by Cohen and Cohen to allow for continuous predictors (i.e., HRV). In the current research, we implemented repeated measures regression in SAS PROC GLM such that spatial frequency and emotion were within-subjects factors and HRV was a between-subjects factor. For balanced designs, repeated measures regression results in the same *F*-values as multi-level models (see Misangyi et al., 2006).

2.2. Results

Based on previous research (Collin and Mcmullen, 2005), we expected that participants would be more accurate for BSF faces compared to HSF or LSF faces. To test this hypothesis, we conducted a 3 (spatial frequency: broad, high, low) × 2 (emotion: fearful, neutral) repeated measures ANOVA on response accuracy. Spatial frequency and face emotion were within-subject factors. As predicted, participants were more accurate for BSF (M = 97%), than for HSF (M = 91%) or LSF (M = 92%), faces, $F(2, 43) = 36.71$, $p < .01$, $\eta_p^2 = .25$. Although previous research suggested that participants utilize more LSF information when identifying the emotion of hybrid face stimuli (Schyns and Oliva, 1999), there was no difference between accuracy for HSF and LSF faces, possibly because we did not use hybrid stimuli. Participants were also more accurate for neutral (M = 94%) than for fearful (M = 93%) faces, $F(1, 43) = 11.07$, $p < .01$, $\eta_p^2 = .05$. However, these effects were qualified by a spatial frequency × emotion interaction, $F(2, 43) = 3.04$, $p < .05$, $\eta_p^2 = .03$ (see Table 1). Simple effects indicated that participants were more accurate for neutral than fearful LSF faces ($p < .01$), but not BSF ($p = .77$) or HSF ($p = .17$) faces.

We expected that HRV would be associated with accuracy discriminating fearful, but not neutral, faces. The predicted emotion × HRV interaction was found, $F(1, 42) = 18.56$, $p < .01$, $\eta_p^2 = .08$, indicating that HRV was positively correlated with accuracy for fearful ($r = .24$, $p < .01$), but not neutral ($r = -.10$, $p = .28$), faces.

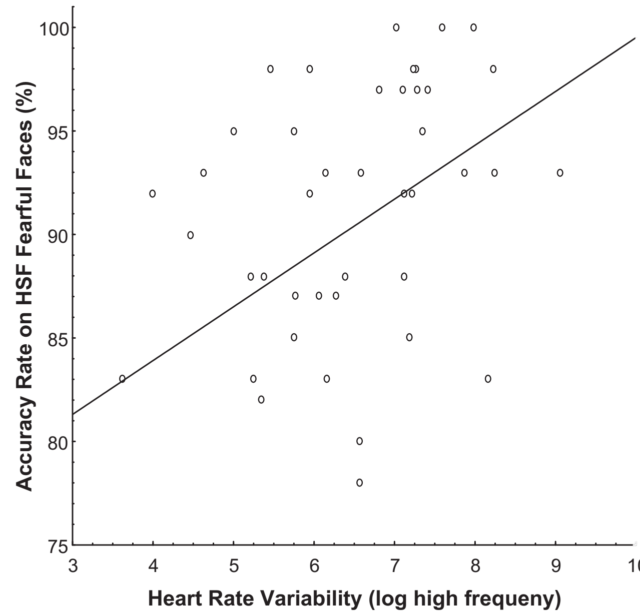

Fig. 3. A scatterplot indicating the positive correlation between HRV (*x*-axis) and accuracy discriminating HSF fearful faces (*y*-axis) in Experiment 1 (the emotion discrimination task). $r = .40$, $p < .01$.

As predicted, there was a significant three-way interaction between HSF, emotion, and HRV, $F(1, 42) = 10.01$, $p < .01$, $\eta_p^2 = .05$,[2] and a marginally significant three-way interaction between LSF, emotion, and HRV, $F(1, 42) = 3.46$, $p = .06$, $\eta_p^2 = .01$.[3] To decompose these interactions, we examined the main effects and interaction between emotion and HRV for BSF, HSF and LSF, separately. At HSF, a predicted emotion × HRV interaction, $F(1, 42) = 9.62$, $p < .01$, $\eta_p^2 = .19$, indicated that HRV was more positively correlated with accuracy for fearful ($r = .40$, $p < .01$; see Fig. 3) than neutral ($r = -.16$, $p = .31$) faces. At LSF, an emotion × HRV interaction, $F(1, 42) = 4.97$, $p = .03$, $\eta_p^2 = .11$, indicated that HRV was marginally more positively correlated with accuracy for fearful ($r = .26$, $p = .08$) than neutral ($r = -.18$, $p = .25$) faces. At BSF, there was no interaction between HRV level and emotion, $F(1, 42) = 0.28$, $p = .60$, $\eta_p^2 = .01$, indicating that HRV was not differentially correlated with accuracy for fearful ($r = .04$, $p = .78$) versus neutral ($r = .15$, $p = .32$) faces. Thus, people with high HRV were significantly more accurate than those with low HRV at identifying the specific emotion of HSF fearful faces.

2.3. Discussion

This experiment provides initial evidence that vagally mediated HRV is associated with the perceptual discrimination of affectively significant stimuli at high spatial frequency. We found that higher HRV is associated with superior accuracy discriminating HSF fearful faces, which is considered to be difficult and is associated with cortical function. This result extends previous research by showing that HRV is associated with the visual discrimination of affectively significant facial expressions at high spatial frequency. There is some evidence that HRV is associated with accuracy discriminating

[2] When we used a more complex hierarchical linear model in which we predicted hits on HSF fear trials after adjusting for the false positive responses, the three-way interaction was still significant, $F(1, 42) = 6.76$, $p < .01$, $\eta_p^2 = .03$. It is important to note that these three-way interactions on reaction time were not statistically significant ($ps > .46$).

[3] However, in a hierarchical linear model adjusting for false positive responses, the three-way interaction between LSF, HRV and emotion dropped to non-significant ($p = .10$).

LSF fearful faces, but the relationship disappears with a hierarchal model adjusting for the false positive responses. HRV is not associated with performance on discriminating BSF fearful faces.

3. Experiment 2

In Experiment 2, we examined whether the relationship between HRV and the discrimination of HSF fearful faces could be attenuated by a different processing goal. To address this question, we had participants perform an expressiveness task in which they were instructed to determine whether a face was expressive or not (Schyns and Oliva, 1999).

3.1. Methods

3.1.1. Participants

Thirty-six undergraduate students successfully completed the study for partial course credit. None participated in Experiment 1 to avoid potential carry-over effects (see Experiment 2 in Schyns and Oliva, 1999). We followed the same procedure of recruiting participants as in Experiment 1. We excluded data from one participant who had more than 15% missing trials due to errors and outliers, yielding 35 participants (19 women; mean age = 20).

3.1.2. Design, stimuli, procedure, physiological measurements and analyses

The design, stimuli, procedure, measures and analyses were identical to Experiment 1, with the exception that participants were instructed to determine whether stimuli were expressive or not on each trial (Schyns and Oliva, 1999).

To assess whether individual differences in HRV were associated with task performance, we created separate dummy-coded variables for facial emotion (fear = 1, neutral = 0), and low (LSF = 1, BSF = 0, HSF = 0) and high (LSF = 0, BSF = 0, HSF = 1) spatial frequency, using BSF as a reference group. We also mean-centered HRV and computed interaction terms between these variables (Aiken and West, 1991). We conducted a facial emotion (neutral, fear) × low spatial frequency (low, other) × high spatial frequency (high, other) × HRV (continuous) multiple regression analysis on response accuracy.

3.2. Results

As in Experiment 1, we conducted a 3 (spatial frequency: broad, high, low) × 2 (emotion: fearful, neutral) repeated measures ANOVA on response accuracy. Spatial frequency and face emotion were within-subject factors. Replicating the results of Experiment 1, participants were more accurate for BSF (M = 96%), than for HSF (M = 91%) or LSF (M = 91%), faces, $F(2, 34) = 12.78$, $p < .01$, $\eta_p^2 = .13$, although emotion, $F(1, 34) = .40$, $p = .53$, $\eta_p^2 = .00$, and the spatial frequency × emotion interaction, $F(2, 34) = 2.48$, $p < .09$, $\eta_p^2 = .03$, were not statistically significant (see Table 2).

In contrast to results in Experiment 1, the three-way interaction between HSF, emotion, and HRV was *not* significant ($p = .67$).[4] This null effect suggests that processing goals may moderate the relationship between HRV, emotion, and high spatial frequency identified in Experiment 1. Contrary to our prediction, the three-way interaction between LSF, emotion, and HRV ($p = .88$) was not statistically significant (nor were any of the two-way interactions; $ps > .18$).[5]

[4] In addition, the two-way and three-way interactions on reaction time were not statistically significant ($ps > .38$).

[5] In addition, the two-way and three-way interactions on reaction time were not statistically significant ($ps > .62$).

Table 2
Means and standard deviations of percentage of response accuracy and reaction times (in milliseconds), as a function of types of spatial frequency and emotion in the expressiveness discrimination task (Experiment 2).

			Mean	SD
BSF	Fearful	Accuracy	96.1	4.9
		RTs	673.4	92.0
	Neutral	Accuracy	95.2	4.7
		RTs	695.7	95.0
HSF	Fearful	Accuracy	92.4	8.4
		RTs	722.7	98.1
	Neutral	Accuracy	89.7	8.1
		RTs	747.3	93.6
LSF	Fearful	Accuracy	90.1	8.8
		RTs	704.7	103.7
	Neutral	Accuracy	92.0	8.8
		RTs	727.3	99.2

3.2.1. Comparing task effects

Due to the lack of statistical power, there is a reasonable probability that the research design was not sensitive enough to detect effects (see Cohen, 1988). Therefore, we decided to test our hypothesis empirically by comparing the results from the two experiments. We conducted a 2 (facial emotion: neutral, fear) × 2 (low spatial frequency: low, other) × 2 (high spatial frequency: high, other) × continuous (HRV) × 2 (task: emotion discrimination, expressiveness) multiple regression analysis on response accuracy. All factors were within-subjects except task type and HRV, which were between-subjects. As predicted, we found a significant four-way interaction between HSF, emotion, HRV and task, $F(1, 75) = 5.03$, $p < .03$, $\eta_p^2 = .01$. To directly compare the effects of HRV on accuracy for HSF fearful faces, we conducted a continuous (HRV) × 2 (task: emotion discrimination, expressiveness) multiple regression analysis on response accuracy for HSF fearful faces. As predicted, a significant HRV × task interaction, $F(1, 75) = 5.98$, $p < .02$, $\eta_p^2 = .07$, indicated that the correlation between HRV and accuracy was higher in Experiment 1 ($r = .40$, $p < .01$) than Experiment 2 ($r = -.13$, $p = .47$). When we compared the resting HRV between two groups, there was no difference, $t(77) = -.43$, $p = .67$, $d = .15$. Taken together, these results are consistent with our prediction that the relationship between HRV and response accuracy for HSF fearful faces in the emotion discrimination task was attenuated in the expressiveness task.

3.3. Discussion

In Experiment 2, the relationship between HRV and the perceptual discrimination of HSF fearful faces was attenuated when participants were asked to discriminate the *expressiveness* of faces. Specifically, these null results involving HSF fearful faces suggested top-down modulation; to test this hypothesis directly, we compared the two experiments. The significant interaction between HRV and task type revealed that the relationship between HRV and performance on HSF fearful faces in the emotion discrimination task (Experiment 1) was no longer apparent in the expressiveness task (Experiment 2). The processing goal associated with the expressiveness task may override the positive relationship between HRV and the emotional discrimination of HSF fearful faces (see Schyns and Oliva, 1999). However, contrary to our prediction, there was no relationship between HRV and LSF fearful faces.

4. General discussion

Two experiments provided evidence that resting HRV—which is considered to be an index of autonomic, cognitive, and emotional self-regulation (Friedman, 2007; Thayer and Friedman, 2004; Thayer and Lane, 2000; Thayer et al., 2009)—is correlated with the perceptual discrimination of HSF fearful faces, but this correlation is sensitive to processing goals. Specifically, HRV was positively correlated with discriminating HSF fearful facial expressions when participants were asked to discriminate the *emotion* of faces. However, when participants were asked to discriminate the *expressiveness* of faces, the relationship between HRV and HSF fearful faces was eliminated.

These experiments provide initial evidence that HRV is correlated with visual discrimination of fearful faces at high spatial frequency. Discriminating emotions of HSF fearful faces is proposed to be a difficult task (Mermillod et al., 2008), which may require the recruitment of executive function (such as focused attention) mediated by the prefrontal cortex (Vuilleumier et al., 2003; Winston et al., 2003). Consistent with this view, our results showed that participants with high HRV were better at discriminating HSF fearful faces. Furthermore, a recent study by our group showed that individual differences in HRV were associated with the functioning of the inhibition of return (IOR) in response to HSF fearful faces (Park et al., 2012). IOR is the attentional phenomenon that prevents one's attention from going back to previously attended locations and preferably explores new locations, thereby enhancing visual search (Posner et al., 1985; Stoyanova et al., 2007; Sumner, 2006). In the study, HRV was associated with the superior ability to inhibit attention from HSF fearful faces and to instigate novelty search. People with higher HRV may benefit from the ability to accurately discriminate HSF fearful faces when it is necessary to inhibit them for novelty search.

Processing low spatial information is primarily associated with subcortical mechanisms, such as the amygdala, and therefore is considered to be optimal for emotional discrimination (Mermillod et al., 2008; Pessoa, 2005; Vuilleumier et al., 2003). Discriminating emotions using low spatial frequency information is an easy task that requires less executive control. Our results showed that HRV was marginally associated with accuracy discriminating LSF fearful faces, but the relationship disappeared in a hierarchal model after adjusting for false positive responses.

The ability to discriminate affectively significant stimuli (e.g., fearful faces) plays an important role in social interactions and emotional self-regulation. Evidence that high HRV is associated with superior perceptual discrimination of affectively significant stimuli is consistent with previous research showing that people with higher HRV have more adaptive patterns of emotional responding and self-regulation, whereas people with lower HRV have trouble differentiating safety versus threat signals (Friedman, 2007; Thayer and Friedman, 2004; Thayer et al., 2009). The capacity for perceptual discrimination may affect not only emotional self-regulation, but also physiological health. The inability to accurately discriminate threatening stimuli may result in the constant activation of defensive behavior mechanisms, which may be associated with physiological, as well as emotional, problems (Thayer and Lane, 2000). It has been well documented that low levels of HRV are associated with physiological problems such as hypertension, diabetes, high cholesterol, obesity, arthritis, and some cancers, as well as various affective disorders including panic disorder and generalized anxiety disorders (Friedman and Thayer, 1998; Thayer et al., 1996).

The results of Experiment 2 suggest that processing goals can alter the relationship between HRV and the visual discrimination of HSF fearful faces. It has been suggested that people utilized HSF information when determining the expressiveness of faces (Schyns and Oliva, 1999). Thus, it becomes easier to discriminate the expressiveness of HSF faces and may require relatively less prefrontal control. This helps explain why the positive relationship between HRV and performance on HSF fearful faces exhibited in the emotion discrimination task was no longer significant. Although we expected HRV would be associated with LSF faces in the expressiveness task, there was no significant relationship between HRV and performance discriminating LSF faces in Experiment 2. Participants might have attended to emotional aspects of the faces, at least to some degree, when discriminating expressiveness of faces. As a result, it becomes easier to detect expressiveness of LSF information. Along the same lines, it is also possible that participants used an index of expressiveness (e.g., big eyes) to identify emotions in the emotion discrimination task. Nonetheless, the relationship between HRV and visual perception of HSF faces was influenced by task type. This is consistent with the diagnostic model of perception (Schyns, 1998; Schyns and Oliva, 1999), which proposes that the perception and utilization of spatial frequency information is not fixed, but flexible, and may be modulated by cognitive constraints to select and discriminate specific information. For example, Schyns et al. (2002) reported that the use of fine-scale, HSF information is different across tasks, whereas the use of coarse LSF information is less sensitive to task type. The results of our experiments suggest that the use of HSF information is modulated not only by task, but also by individual differences in HRV.

There are some limitations of the current research. Individual differences in acuity, such as accommodation responses (both phasic and tonic), and potentially uncorrected hyperopia, may have contributed to the findings. There is evidence suggesting that vagal activity is associated with visual focusing (accommodation) responses (Chen et al., 2003; Tyrrell et al., 1995), which may in part explain the relationship between HRV and performance on discriminating HSF fearful faces. Since we did not measured visual acuity or accommodation, we cannot examine whether individual differences in acuity might have played a role in our results. However, in the present study, the relationship between HRV and discriminating HSF faces is limited to fearful expressions and the relationship is modulated by task type. Therefore, even if individual differences in acuity might have played a role in the study, they could not fully account for these differences across task type. Still, the possibility cannot be completely ruled out and it is important to measure participants' visual acuity more extensively in future research.

The current research provided initial evidence that cardiac vagal tone, a mechanism by which cortical activity modulates cardiovascular function, is positively associated with superior visual discrimination of affectively significant stimuli. Moreover, the relationship between the heart and visual perception is sensitive to the top-down influence of different processing goals. This suggests that perception and peripheral physiology are not only tightly related, but also remarkably flexible.

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