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Effect of parasympathetic stimulation on brain activity during appraisal of fearful expressions

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ABSTRACT

Autonomic nervous system activity is an important component of human emotion. Mental processes influence bodily physiology, which in turn feeds back to influence thoughts and feelings. Afferent cardiovascular signals from arterial baroreceptors in the carotid sinuses are processed within the brain and contribute to this two-way communication with the body. These carotid baroreceptors can be stimulated non-invasively by externally applying focal negative pressure bilaterally to the neck. In an experiment combining functional neuroimaging (fMRI) with carotid stimulation in healthy participants, we tested the hypothesis that manipulating afferent cardiovascular signals alters the central processing of emotional information (fearful and neutral facial expressions). Carotid stimulation, compared to sham stimulation, broadly attenuated activity across cortical and brainstem regions. Modulation of emotional processing was apparent as a significant expression-by-stimulation interaction within left amygdala, where responses during appraisal of fearful faces were selectively reduced by carotid stimulation. Moreover, activity reductions within insula, amygdala, and hippocampus correlated with the degree of stimulation-evoked change in the explicit emotional ratings of fearful faces. Across participants, individual differences in autonomic state (heart rate variability, a proxy measure of autonomic balance toward parasympathetic activity) predicted the extent to which carotid stimulation influenced neural (amygdala) responses during appraisal and subjective rating of fearful faces. Together our results provide mechanistic insight into the visceral component of emotion by identifying the neural substrates mediating cardiovascular influences on the processing of fear signals, potentially implicating central baroreflex mechanisms as for anxiolytic treatment targets.

Keywords: autonomic, baroreceptor, carotid stimulation, emotion, fear, visceral, neuroimaging

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INTRODUCTION

Influential theories emphasize the contribution of bodily arousal to emotion and affective feelings ([James, 1894](#); [Barrett et al., 2007](#); [Damasio, 1994](#); [Dolan, 2002](#)). Even without a specific mapping of bodily state to emotional type (e.g. Cannon, 1927), the cognitive interpretation of a change in bodily arousal can shape the emotional experience ([Schachter and Singer, 1962](#); [Barrett, Lindquist and Gendron, 2007](#)). Improved anatomical and functional description of bidirectional interactions between body and brain has advanced our understanding of emotional mechanisms ([Craig, 2002](#); [Critchley et al., 2002, 2004; 2005a, 2005b](#); [Harrison et al., 2009](#)) and, for some emotions, there is good evidence of specific coupling with autonomically-mediated changes in peripheral physiology ([Ekman et al., 1983](#); [Harrison et al., 2006](#)).

There is particular interest in the relationship between parasympathetic control of the heart and emotion. Here, heart rate variability (HRV) (derived from electrocardiography; ECG) indexes the parasympathetic regulation of the heart via the vagus nerve and reflects the degree to which the cardiac activity can be modulated to meet changing situational and emotional demands ([Thayer and Lane, 2000](#); [Thayer and Brosschot, 2005](#)). Moreover, it is closely linked to individual differences in emotional responding, and capacity for self-regulation (see [Friedman, 2007](#); [Thayer et al., 2009](#)). Increased HRV is associated with adaptive emotional responses to threat ([Thayer and Lane, 2000](#); [Thayer et al., 2009](#)) and increased sensitivity to the emotions of others ([Quintana et al., 2012](#)).

The human amygdala mediates interaction between the body and the brain during affective processing. The amygdala supports the perception of fear signals and threat ([Zald, 2003](#); [Phelps and LeDoux, 2005](#)) and its activity correlates with emotional intensity rating of affective pictures ([Phan et al., 2004](#)), including facial expressions ([Hamann and Mao, 2002](#)). Outputs from the amygdala innervate hypothalamic and brainstem autonomic circuits to

trigger autonomic arousal responses to emotional challenges, particularly threats (LeDoux, 2000). Amygdala-induced autonomic arousal is expressed as increased sympathetic activity and/or decreased HRV (Critchley et al., 2005b; Gianaros et al., 2012). The amygdala is also sensitive to feedback from the periphery regarding state of bodily arousal (Critchley et al., 2002).

Carotid baroreceptors signal the state of cardiovascular arousal to the brain: when arterial blood pressure rises, baroreceptors drive afferent neuronal firing to evoke a reflex-mediated increase in parasympathetic activity and a decrease in sympathetic activity (Sagawa, 1983; reviewed Fadel et al., 2003). This natural fluctuations in baroreceptor activity (with cardiac cycle) can influence different cognitive functions. Cardiac cycle has modulatory effects on simple reaction time in different sensory modalities (Edwards et al., 2008), somatosensory thresholds (Wilkinson et al., 2013), on memory for words (Garfinkel et al., 2013) and processing of fear (Garfinkel et al., 2014). While the literature argues for an inhibitory effect of systole, recent data (Garfinkel et al., 2014) show an enhancing effect on fear processing, and others report reduction of somatosensory thresholds (e.g. Wilkinson et al., 2013; Edwards et al., 2008). Speculatively these discrepancies suggest two competing mechanisms that may reflect different roles and afferent channels (cranial nerves IX and X respectively) of carotid and cardiac baroreceptors. In fact, diastolic activation of low pressure cardiac baroreceptors during cardiac filling is known to inhibit neurons within the locus coeruleus (Morilak et al., 1986; Jacobs et al., 1991).

Artificial mechanical stimulation of baroreceptor activity also demonstrates interaction between autonomic and cognitive/emotional processes (Basile et al., 2013a; 2013b; Calcagnini et al., 2010). A non-invasive, automated neck suction device enables carotid stimulation (CS) to be implemented concurrently with functional magnetic resonance neuroimaging (fMRI): neck suction stimulates carotid baroreceptors by increasing transmural

pressure within the carotid sinus (Cooper and Hainsworth; 2009). This evokes an enhanced parasympathetic cardiovascular drive via the baroreflex. Previous studies from our group show that the same CS procedure modulates activity within brain areas including amygdala and insula in brain at rest, when engaged in a cognitive task, or during emotional processing (Basile et al., 2013a; 2013b).

Motivated by recent observations regarding the influence of cardiac cycle on fear processing (Garfinkel et al., 2014), the aim of the present study was to investigate the effect of a direct parasympathetic perturbation by CS on neural and subjective responses to the appraisal of fearful (compared to neutral) facial expressions. Further, we test whether individual traits in basal vagal tone (expressed as resting HRV) predict the degree to which this perturbation of viscerosensory autonomic function influences fear processing. Based on extant literature, we hypothesized a priori specific involvement of amygdala, insula, periaqueductal grey (PAG) as regions of interest supporting interaction between fear processing and our experimental physiological manipulation.

MATERIALS AND METHODS

Participants

Twenty-one right-handed volunteers (12 females/ 9 males; mean age = 27.3 years; SD = 2.6; range, 23–32) with no neurologic, psychiatric disorders and other major clinical conditions, underwent detailed autonomic examination, including electrocardiogram, assessment of arterial pressure and respiratory frequency during the Valsalva manoeuvre and orthostatic challenge, indicating no sign of autonomic dysfunction. The study was approved by the Santa Lucia Foundation ethical committee. Written informed consent was obtained from all participants.

Heart rate variability (HRV) evaluation

HRV analysis of normal interbeat intervals was used to index autonomic balance biased toward parasympathetic activity (Malik and Camm, 1995; Heart rate variability, 1996). The evaluation of the autonomic system consisted in the Valsalva manoeuvre performed consecutively for three times, with a two minute rest, followed by a ten minutes orthostatic and supine ECG recording. The results obtained from three-minute recordings (extracted randomly) did not differ from the results obtained from 10 minute recordings, allowing us to estimate the HRV on the basis of short time recordings. Two datasets, corresponding to three stable consecutive minutes of supine and orthostatic recordings, were analysed using an autoregressive model (Baselli et al., 1987; Howorka et al., 2010).

Normal sinus to normal sinus (N-N) interbeat intervals were extracted to derive: 1) time domain measures (variance of N-N intervals) and 2) frequency domain measures (power spectral density measures indexing distributed variance of N-N intervals as a function of frequency).

Within the time domain, we calculated the standard deviation of N-N intervals (SDNN), the square root of the mean of the squares of the differences between adjacent N-N intervals (rMSSD), the number of differences between successive N-N intervals greater than 50 ms (NN50), the percentage of differences between adjacent N-N intervals that are >50 ms (pNN50).

The total power densities and the main power densities within high-frequency (HF) (0.15–0.4 Hz), low-frequency (LF) (0.04–0.15 Hz) and very low frequency (VLF) (0.003 - 0.04 Hz) bands were quantified in absolute values of power (ms^2).

Paradigms and procedure

An event-related design, including two runs with 80 trials (total number of trials=160), randomly administered over 19.5 min of fMRI acquisition was used in this experiment (total experiment duration approximately 40 min; Fig. 1A). Within each run, 40 fearful and 40 neutral faces were randomly presented. The trials lasted on average 9700 ms each (range 9200-10200) ms, followed by a variable inter-trial interval (ITI), lasting on average 4 s (range 3050 – 4950 ms) in 80% of the trials, and 9 s (range 8050 – 9950 ms) in 20% of the trials.

During the fMRI, each participant was presented with emotional and neutral faces from the Ekman set (Ekman and Friesen, 1974). First, a fixation cross appeared for 1 sec, followed by brief presentation of a face stimulus (200 ms)¹. A total of 80 fearful and 80 neutral faces were randomly presented over two runs. A post-stimulus fixation cross was then presented for 500 ms, followed by a blank screen with a 'ready' message (3 – 4 sec). A visual analogue scale (VAS) was then presented for 3500 ms for the participant to rate emotional

¹ The 200 ms period was selected for because it would allow comparison with planned studies on natural baroreceptor activation within the cardiac cycle.

intensity of the face ² on a scale ranging from 0 – no emotional intensity- to 100 –extreme emotional intensity (see Fig.1). There was a variable inter-trial interval lasting on average 4000 ms (range 3050 – 4950 ms) for 80 % of the trials and 9000 ms (range 8050 – 9950 ms) for 20 % of the trials.

Carotid stimulation delivery

Using a laboratory-built device for MRI, neck suction was delivered through two individual cuffs within a neck collar (see Basile et al, 2013a,b; Calcagnini et al., 2010). The pressure was set by controlling the aspiration level of a vacuum source (placed in the MRI control room) by a PC. The actual pressure within each cuff of the neck collar was continuously and independently monitored. Specific placement of neck suction cuffs was tailored for each participant, using carotid angiograms acquired earlier to localise points of carotid artery bifurcation. CS was delivered in pulses of variable duration, ranging from 7200 to 8200 ms. In order to assure an efficient influence of the ANS perturbation on the emotional elaboration of the faces, the CS was time-locked to the onset of the face stimulus and offset of the VAS. Periods of efficacious (-60 mm Hg pressure) and non-efficacious (-10 mm Hg pressure) CS were randomly delivered. Active pulses were always followed by an ITI of a variable duration (Fig 1 A1), during which CS was not delivered and participants were not engaged in any active task. This reduced the likelihood of baroreceptor response accommodation.

Physiological signal acquisition and analysis

ECG, pulseoximetry, and respiration were recorded during fMRI (Biopac Systems Ins, CA). N-N interbeat intervals were extracted from the ECG. Cardiovascular response to

² In this study, emotional intensity refers to the intensity of emotional experience that the facial expression evokes in the participant. In the case of neutral faces, based on previous studies, we assume that an inexpressive face is not necessarily an emotionally neutral stimulus and could, therefore, trigger an emotional experience in the individual (Phillips et al., 1997).

CS was assessed as the percentage difference between the average N-N interval during the neck suction and the average N-N interval during the preceding inter trial interval. No motion artefacts were detected when the CS was applied using the two-cuff device. Physiological monitoring and CS delivery did not induce an increase in radio frequency noise.

fMRI acquisition and preprocessing

Neuroimaging data was acquired using a head-only 3.0T MR scanner (Siemens Magnetom Allegra, Siemens Medical Solutions, Erlangen, Germany). Functional brain images optimised for blood oxygenation level dependent (BOLD) contrast were collected using an echo-planar T2*-weighted sequence (TR=2.08s, 32 axial slices, slice thickness=2.5mm, gap=1.3mm). Data were processed using MATLAB 7.0 (MathWork, Natick, MA) and SPM8 (Statistical Parametrical Mapping, <http://www.fil.ion.ucl.ac.uk>). In both experiments, the first four volumes were discharged to allow for T1 equilibration effects

EPI images were realigned to the first image and normalized to a standard echoplanar image template. Normalized functional scans were smoothed with a Gaussian kernel of 8-mm (full-width half maximum).

Data analysis

A repeated measures 2x2 ANOVA was conducted to test the effect of CS on emotional processing. CS (efficacious-ON, non-efficacious-OFF) x emotion (fear, neutral) was entered as within-participant variables. **A high-pass filtering to 1/128 Hz was applied to remove low-frequency noise**

The stimulation-by-emotion interaction effect on ratings was then explored using post-hoc t-tests Bonferroni-corrected for multiple comparisons. Further, we performed a

median-split analysis to explore for differences in physiological measure in the group of participants, based on their performance on the behavioural task.

First-level analyses estimating contrasts of interest for each participant were followed by second-level mixed-effect analyses for statistical inference at the group level (Friston et al., 2002).

The first-level multiple regression model included eight conditions, four corresponding to the face event and four corresponding to the VAS task, in both cases reflecting a combination of emotion (fear, neutral) and CS (ON,OFF), which were modelled and convolved with a canonical haemodynamic response function. The four face event conditions were modelled as miniblocks, time-locked at the onset of the face with a duration of 200 ms, whereas the four VAS conditions were time-locked at the onset of the VAS rating event with a duration of 3500 ms. All predictors were convolved with the SPM8 hemodynamic response function, and realignment parameters were included as covariates of no interest.

At the group level, two different analyses were carried out. In a first analysis, the four conditions resulting from the emotion x CS combination (of both the face event and the VAS period) were modelled within a 2 x 2 within-participant ANOVA, to test for the main effect of the stimulation (ON < OFF; ON > OFF) across emotional conditions, and for the interactions between the two factors [(fearON<OFF) -(neutralON<OFF)]. A correlational analysis was then carried out between the difference between fearful [ON - OFF] and neutral ratings [ON - OFF] and brain activity during the VAS task. The statistical threshold was set to $p < 0.05$, FWE corrected at the voxel level for whole brain.

Moreover, for the region-of-interest (ROI) analyses, anatomical masks were constructed using the anatomical toolbox in SPM (Tzourio-Mazoyer et al., 2002) for bilateral insula. A sphere (6 mm radius) was applied on the region of the periaqueductal grey (PAG),

based on MNI coordinates [0 -28 -9] and a 10 mm radius sphere on the amygdala based on coordinates [32 0 -24] from Garfinkel et al., (2014). Statistical threshold was set to $p < 0.05$ - FWE-corrected at cluster level (cluster size defined using uncorrected voxel-level threshold $p < 0.005$).

Next, we tested whether the areas showing an effect of CS over emotional appraisal were associated with basal HRV measures. We considered a sphere (10 mm radius) centred on peak voxel within the ROI analyses described above. The association between contrast estimates from our ROIs and HRV measures were evaluated using Pearson correlations.

RESULTS

As expected, all subjects (but one) had an increase of R-R intervals during the efficacious stimulation (see Figure S1 for the individual response to efficacious CS). Thus, efficacious CS engendered a significant increase in the interbeat (R-R) interval indicating autonomic perturbation (average increase in R-R interval: 19.2 ms; pre vs. during CS, $t(20) = 8.4$, $p < 0.001$). Non-efficacious CS resulted in a non-significant increase of 6.0 ms in (pre vs. during CS, $t < 1$).

Behavioural results

We observed a significant main effect of emotion, reflecting greater intensity ratings for fear faces relative to neutral faces [$F(1, 18) = 334.9$, $p < 0.001$], and no main effect of CS [$F(1, 20) < 1$] on intensity ratings. Importantly, we observed a significant CS-by-emotion interaction [$F(1, 20) = 14.8$, $p < 0.001$].

The efficacious CS induced a positive shift (i.e. higher) emotional intensity rating; efficacious-ON = 33.79, SD= 15.66 vs. non-efficacious-OFF 32.07, SD= 18.99) for neutral

faces in most of the participants (Figure 1, Panel B1). Planned contrasts for each emotion type revealed a trend in the effect of CS on appraisal of neutral expressions (18/20 positive events, two-tailed sign test $p < 0.01$). Across the group, there was no overall significant difference for fearful expressions (efficacious-ON = 66.73, SD= 20.30 vs. non-efficacious-OFF 68.45, SD= 14.67; $t(20) = 1.2$, $p = 0.1$). However, during the appraisal of fearful stimuli, 10 participants exhibited a positive shift and 11 participants exhibited a negative shift.

We therefore performed a median-split of participants to compare HRV measures of the participants exhibiting a positive shift and those exhibiting a negative shift. Participants with a positive shift in fearful rating manifest higher basal vagal parasympathetic tone compared to those with a negative shift, expressed as higher HF spectral power and rMSSD, NN50 and pNN50 HRV time-domain indices (Figure 1, B2). Therefore, when controlling for the basal vagal activity of each participant, a significant difference emerged for fear ratings when comparing ON vs. OFF conditions (66.73 vs. 68.46, $F(1, 19) = 4.96$, $p < 0.05$).

Relation to HRV parameters

HRV parameters correlated with the magnitude of the behavioural expression of the stimulation-by-emotion interaction on intensity ratings ($[\text{fearON-OFF}] - [\text{neutralON-OFF}]$) (Figure 1, B3). A positive correlation was evident between the behavioural interaction and time domain measures of parasympathetic response: NN50 ($r = 0.48$, $p < 0.02$), pNN50 ($r = 0.50$, $p < 0.03$). Similarly, this behavioural interaction negatively correlated with LF ($r = -0.49$, $p < 0.03$) and VLF spectrum ($r = -0.55$, $p < 0.01$), yet positively correlated with HF spectrum ($r = -0.65$, $p < 0.02$). In all the cases, the interaction was driven by a correlation with the simple effect of CS on perceived intensity of fear stimuli (fear ON-OFF; pNN50 $r = 0.49$; HF $r = 0.48$, VLF $r = -0.57$, LF $r = -0.47$; all $p < 0.05$), whereas no correlation was evident with the effect of CS on neutral ratings (neutral ON-OFF). This result extends the findings of the

median-split analysis to indicate that the individual basal vagal activity differently affected the modulation of emotional ratings by CS: Individuals with higher basal HRV exhibited a positive shift in the rating of fearful faces during the ON condition. Notably, the same influence was not evident during the neutral rating condition. In order to examine whether the carotid effect was confined among participants with high or low HRV, a second median-split control analysis was conducted, splitting the group in 'high' and 'low' HRV participants. The difference between ON and OFF in rating of fearful expressions was coherent with the first median split analysis, i.e. the group of "high HRV" group reported a positive shift in fearful rating during CS ON whereas the "low HRV" group reported a negative shift, although both effects were not significant ($p < 0.1$ one-tailed t test) (see Supplementary material for a graphic representation, Figure S2).

Neuroimaging results

Main effect of efficacious carotid stimulation: A whole-brain neuroimaging analysis was conducted to test the effect of CS during the appraisal of facial expressions (i.e. VAS rating period), although exploratory analysis has been conducted to test the effect of CS on perception of facial expressions (i.e. face presentation event, see Figure 1).

Consistent with our knowledge concerning the delay in effects of maximum baroreceptor stimulation with this method from our previous studies (e.g. Basile et al., 2013), we anticipated effects to emerge after the face stimuli were presented. The analysis focused on the VAS event revealed a significant main effect of CS during the rating of face stimuli, irrespective of emotion for stimulation $ON < OFF$ (see Table 1) manifest as a distributed decrease in brain activity during efficacious stimulation in the following areas: bilateral hippocampus, bilateral amygdala, left thalamus, temporal fusiform areas (see Figure 2 and

Table 1 for the complete list of brain areas). The ROI analysis revealed a significant effect also in bilateral insula. No positive effects of efficacious CS on brain activity (ON>OFF) were evident.

As regards the face perception, the results are marginal for the purpose of the current study, and are presented as Supplementary material. Overall, a significant main effect of was evident during face perception, manifested both as an increased neural activity in the lateral occipital cortex bilaterally and a decreased activity in bilateral temporal pole (see Figure S3 and Table S1). Moreover, an increased activity was present during the perception of fearful over neutral faces irrespective of CS, in left occipital fusiform gyrus, left anterior cingulate gyrus and right postcentral gyrus.

Interaction between carotid stimulation and emotional rating condition

We next tested for interaction between CS (ON, OFF) and emotion ([fearON < OFF] v. [neutral ON > OFF]) to investigate the specific effect of CS on emotional appraisal. Conversely, the activity within left amygdala showed a significant CS-by-emotion interaction ($T = 2.88$, 19 voxel, $p < 0.05$ FWE-corrected for small-volume, Figure 2, B1) during the appraisal of facial expressions (i.e. the VAS period). Analysis of the mean activation from left amygdala showed that the interaction ($F(1,20) = 7.42$, $p < 0.01$) was particularly driven by attenuation of amygdala reactivity during CS when appraising the intensity of fear stimuli (fearON vs. fearOFF $t(20) = 4.52$, $p < 0.001$) as no difference was evident when comparing neutralON vs. neutralOFF activation in left amygdala ($t(20) < 1$) (Figure 2, B2).

Consistent with our expectations, we did not observe any significant CS-by-emotion interaction during the perception of faces.

Correlations with emotional ratings

We tested for regions whose activity correlated directly with the behavioural shift induced by CS during fearful and neutral rating. Overall, a positive correlation was evident between changes in the rating of fearful faces [fearful ON – OFF] and the relative attenuation of brain activation by CS. A correlation was evident within bilateral thalamus, hippocampus, cerebellum, middle temporal gyrus, putamen and globus pallidus, frontal orbital cortex, bilateral amygdala and bilateral insula and PAG (see Figure 3A and Table 2 for the complete list of brain areas).

We extracted the mean activation from amygdala, insula and PAG in order to perform additional analyses. A significant correlation was obtained between HRV parameters and amygdala activation during fear rating. Basal LF, HF and RMSSD parameters correlated with activity in left amygdala (LF $r = -0.55$, $p < 0.015$; HF $r = 0.47$, $p < 0.05$; RMSSD $r = 0.45$, $p = 0.05$) and PAG (LF $r = -0.48$, $p < 0.05$; HF $r = 0.52$, $p < 0.05$, Figure 2A). Analysis of the mean activation from left amygdala showed that the individuals that had a negative shift in the rating of fearful faces reported a stronger attenuation in the activity of amygdala and lower basal vagal activity (Figure 3 B).

With neutral faces, a negative correlation was evident between the change in neutral rating [ON – OFF] and in the attenuated activation of PAG during active CS ($T = 3.46$, 7 voxel, $p < 0.037$ FWE-corrected for small-volume, Figure 3C).

DISCUSSION

The aim of this study was to explore how afferent cardiovascular information contributes to the processing of emotion stimuli, notably the fear signals of others. Using stimulation of carotid baroreceptors to perturb parasympathetic drive, we tested for hypothesized effects on the neural processing and appraisal of fearful (relative to neutral) facial expressions. In addition, we explored how individual differences in autonomic state (particularly the basal vagal parasympathetic tone) predicted the influence of CS on emotional processing.

As regards the effect of CS during the appraisal of facial emotions, the observed brain activity is consistent with earlier observations that activation of arterial baroreceptors may inhibit sensory processing and cortical excitability (Koriath et al., 1987).

Here efficacious CS resulted in attenuated activation across cortical and subcortical brain areas during the facial appraisal, including insula, amygdala, hippocampus, thalamus and brainstem. Many of these brain centres are implicated in autonomic regulation (Critchley, 2005a; Kimmerly et al., 2005). In a previous study, our group used the same methodology to describe the modulation by CS of activity within regions, including insula, amygdala and PAG, both at rest and when participants were engaged in a cognitive task (Basile et al., 2013a), or during processing of sad, happy angry and neutral faces (Basile et al., 2013b).

Conversely, the effect of the CS during early events of the trial (i.e. face presentation) affected mainly occipital and temporal areas, consistent with the expected delay in effects of maximum baroreceptor stimulation with this method on our areas of interest (i.e. insula, amygdala, PAG).

A noteworthy aspect of the present study is that CS elicited a differential effect on neural activity during the appraisal of fearful and neutral faces. Activity within amygdala was affected by CS exclusively during the appraisal of fearful faces. In addition, the attenuation of left amygdala activity during the appraisal of fearful expressions predicted the behavioural consequences, as reflected in the magnitude of the behavioural interaction. Thus our results extend mechanistic understanding of the role of the amygdala in the perception and processing of threat, by highlighting the integration of viscerosensory signalling and autonomic control with the neural and behavioural sensitivity to the fear signals of other people ([Zald, 2003](#); [Phelps and LeDoux, 2005](#); [Garfinkel et al., 2014](#)).

These insights were further endorsed by the observation that at the level of individual differences, with individuals with **low basal parasympathetic activity (across HRV-related measures)** manifesting an **decreased perception of fear during the CS**. The degree of change in the behavioural ratings evoked by CS correlated with activity across a set of related regions including insula, amygdala, hippocampus and orbitofrontal cortex. We were particularly interested in the putative role of vagal parasympathetic tone as an index of adaptive emotional regulatory capacity ([Friedman, 2007](#)). Low vagal activity is associated with anticipatory anxiety and hypervigilance towards potential threat ([Thayer et al., 2009](#)), and interestingly those individuals who exhibited a negative shift in fearful ratings during the CS manifest the greatest attenuation of the amygdala activity and had lower parasympathetic tone. We showed this effect also in a direct correlation between HRV measures and attenuation of amygdala and PAG activity when appraising fear faces. These findings strongly endorse the perspective that degree to which viscerosensory afferent information impacts upon both neural reactivity and emotional processing is highly dependent on the integrity of parasympathetic autonomic control and individual characteristics in basal vagal

cardiovascular regulation. Lower vagal activity has been linked to reduced prefrontal inhibitory control over the amygdala (Thayer et al., 2009), and is observed in patients with generalized anxiety disorders, panic disorder and even children of patients with panic disorder (Friedman, 2007 for a review; Srinivasan et al., 2002). Here we show that individuals with lower HRV were more responsive towards the CS, by reporting a stronger deactivation of amygdala and lower rating of fearful stimuli, according to the literature reporting that higher parasympathetic tone is associated with reduced sensitivity to fear perception (Thayer et al., 2009).

Individuals with higher HRV were, conversely, less responsive to CS, showing a less evident effect of the CS on amygdala and a weak positive shift in fearful rating. This raises the possibility that the relationship between parasympathetic tone and fear may not be linear (but instead follows an inverted U-shaped function), or implicates additional mechanisms such as enhanced interoceptive accuracy at lower heart rates (Pollatos et al., 2007). Future research is needed to fully delineate the mechanisms underlying the complex interplay between the basal HRV, stimulation of the parasympathetic tone and the appraisal of emotions.

The influence of baroreceptor afferents on the processing of fearful stimuli was recently investigated by Garfinkel et al., (2014). Here, timing brief fear stimuli to systole, during natural baroreceptor firing, is associated with enhanced processing of fear and corresponding increased neural activity in regions including amygdala. There is moreover an attenuation of the processing of fearful stimuli during diastole. This latter observation may account for the apparent paradoxical findings with present study, where attenuated fear processing (albeit over longer time periods) occurred with the lengthening of inter-beat interval following artificial baroreceptor stimulation. Prolongation of diastole during CS may partly account for these apparently mixed findings, but there remains more to understand

about the timing of baroreceptor influences on emotion and perception. Nevertheless, both studies highlight an important viscerosensory cardiovascular influence, specifically linked to the baroreflex, on the processing of threat signals and fear stimuli. Here, we quantify the neural and behavioural impact of baroreceptor firing on fear processing and extend previous results by noting the dependence of this effect on basal autonomic characteristics of individuals.

Overall, CS showed less pronounced effects on the ratings of neutral faces. PAG activity correlated with stimulation-induced change in the rating of neutral faces. The PAG region is previously implicated in the coupling of peripheral arousal state to emotional processing and expression of fear (Gray et al., 2012; Mobbs et al., 2009; Linnman et al., 2012). Consistently with these previous studies, our data shows that a modulation of the neural activity in the PAG area caused by carotid stimulation results in an increased evaluation of the emotional intensity in neutral faces.

Taken together, our results demonstrate how viscerosensory and autonomic perturbation affect appraisal of fearful and neutral faces at neural and subjective levels. Our study highlights the utility of integrating physiological and neuroimaging techniques to gain detailed insight into mechanisms underlying influential theories of emotion. Our device stimulated the carotid sinus baroreceptors and increased the heartbeat interval, affecting activation across distributed brain areas. Through the use of CS, we directly evaluated the influence of peripheral bodily arousal on emotional appraisal and further demonstrate influence of individual basal vagal tone on these affective processes.

The current study provides not only neurophysiological insights on the interaction between body and brain, but can also potentially contribute to the understanding of pathophysiological conditions, not least the expression and maintenance of anxiety disorders

([Garfinkel et al., 2014](#)), and suggests that treatments for anxiety might target baroreflex-related central pathways.

Accepted manuscript

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The authors declare no conflict of interest.

Accepted manuscript

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Table 1. Brain activation underlying main effect of carotid stimulation, collapsed over specific emotion type**ON < OFF**

Brain region	Cluster		Voxel	
	k	p FWE	Z	MNI xyz
Temporal pole R	31860	0.000*	5.63	34 14 -40
Temporal pole L			5.19	-42 14 -32
Superior frontal gyrus R			5.09	22 20 52
Superior frontal gyrus L			4.89	-20 22 48
Hippocampus L			5.08	-24 -12 -20
Hippocampus R			4.78	26 -10 -22
Postcentral gyrus/precuneus R			5.02	6 -36 58
Postcentral gyrus L			4.44	-44 -12 28
Parahippocampal gyrus R			4.79	36 -32 -14
Amygdala R			4.78	26 4 -24
Amygdala L			4.65	-28 -4 -24
Middle temporal gyrus R			4.72	52 -2 -24
Temporal fusiform area L			4.54	-34 -40 -12
Superior parietal lobule/postcentral gyrus R			4.54	32 -38 46
Thalamus L			4.52	-16 -22 18
Cerebellum, L VI	561	0.009*	3.84	-8 -64 -18
Insula L	9	0.02***#	3.56	-32 -26 16
Insula R	12	0.02***#	3.41	44 -6 -18
Brainstem, midbrain	231	0.001**	4.33	-2 -16 -18

FWE whole brain peak level

* FWE whole brain cluster level

** FWE ROI

Table 2. Brain areas that positively correlated with Δ rating (ON-OFF) of fearful faces**Correlation with fear rating**

Brain region	Cluster		Voxel	
	k	p FWE	Z	MNI xyz
Thalamus R	9182	0.00*	4.89	22 -34 -2
Thalamus L			4.02	-10 -18 12
Temporal occipital fusiform R			4.64	22 -52 -16
Temporal occipital fusiform L			3.89	-36 -56 -14
Hippocampus L			4.51	-24 -24 -6
Putamen			4.21	-32 -4 8
Cerebellum			4.07	-38 -50 -30
Middle temporal pole			3.99	-56 6 -26
Parahippocampal gyrus, posterior L			3.84	-28 -36 -16
Globus pallidum L			3.75	-14 -4 -4
Inferior temporal gyrus L			3.72	56 -56 -14
Frontal orbital cortex			3.45	-38 30 -12
Brain-stem			3.42	10 -20 -22
Postcentral gyrus L	867	0.03*	4.48	-44 -38 60
Superior parietal lobule			2.69	-22 -46 56
Precentral gyrus R	718	0.06*	4.19	46 -4 32
Amygdala L	39	0.003#***	3.92	-36 4 -16
Insula L	24	0.02# **	3.47	-44 -12 6
Insula R	12	0.01# **	3.62	32 -26 -12
PAG	171	0.01# **	3.37	12 -30 -6

FWE whole brain peak level

* FWE whole brain cluster level

** FWE ROI

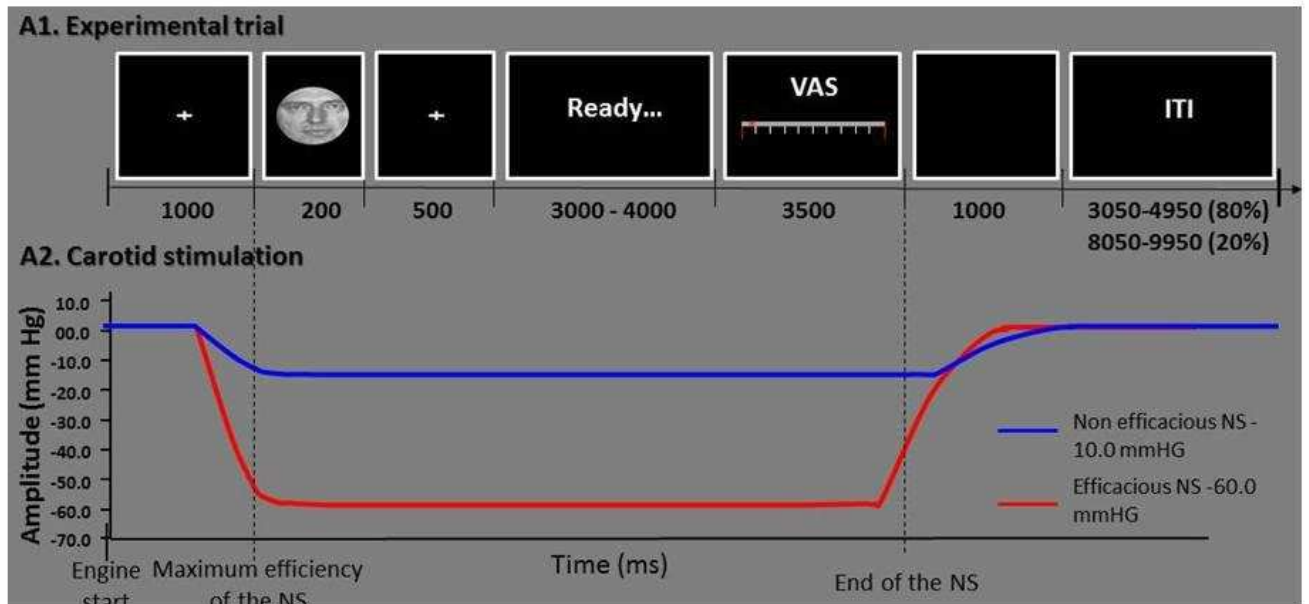
Figure 1. **A) Emotional intensity paradigm.** **A1)** Each trial started with a fixation cross, followed by the presentation of the visual expression (neutral or fearful, 200 ms), and a second fixation cross, a variable “ready” interval, and a VAS task in which the subject had to label faces’ emotional intensity by button pressing on a scale ranging from 0 – no emotional intensity- to 100 –extreme emotional intensity. A variable ITI was introduced at the end of the trial. **A2)** The efficacious (ON) and non-efficacious (OFF) stimulation was randomly delivered to each participant. The neck suction engine started 500 ms after the onset on the pre-face fixation cross, and reached the set value (-10 or -60 mmHG) at the onset of the face. Accordingly, each stimulation offsets at the end of the VAS rating event. **B) Behavioural results.** **B1)** effect of CS during fearful and neutral intensity rating documented on a subject level. The Y axis represents Δ rating [CS ON – OFF] for neutral (left) and fearful (right) faces. Positive values indicate increased ratings during the CS ON condition. For neutral faces (left graph) the majority of participants has a positive shift during CS ON (i.e. increased perceived emotional intensity). In the case of fearful faces, half of the participants exhibited a positive shift and half of the participants exhibited a negative shift (rating of fearful faces lower during CS ON condition). **B2)** Participants with a negative shift in fearful rating reported lower baseline parasympathetic activity, expressed by lower HF spectral power. **B3)** HRV parameters –HF and LF- correlated with the behavioural interaction between CS and emotional rating.

Figure 2. **A)** Main effect of CS (averaged across emotional condition). Notably, brain activity was attenuated during CS in bilateral hippocampus, amygdala and insula (see Table 1 for the complete list of brain areas). **B) B1)** An effect of the CS x emotional condition interaction emerged in the activity of left amygdala. **B2)** The interaction was mainly driven by a attenuation of activity in left amygdala during the rating of fearful faces. **B3)** Graph depicting the significant correlation between the activity in left amygdala and the behavioural interaction between CS and emotional rating condition.

Figure 3. **A)** Graph reporting brain areas significantly correlating with the behavioural shift in fearful rating during CS efficacious stimulation. The activation in left amygdala and PAG correlated with HRV measures, with individuals with higher LF and lower HF indexes reporting stronger attenuation during CS efficacious stimulation. **B)** The correlation between the shift in fearful rating and the neural activation in left amygdale during the appraisal of fearful faces, in individuals having higher and lower HF. Overall, Individuals exhibiting a negative shift in fearful rating had the strongest deactivation of the amygdale and lower parasympathetic tone. **C)** The behavioural shift in neutral rating during CS efficacious stimulation correlated with the activity in PAG area.

Figure 1.

A. Emotional intensity paradigm



B. Behavioural results

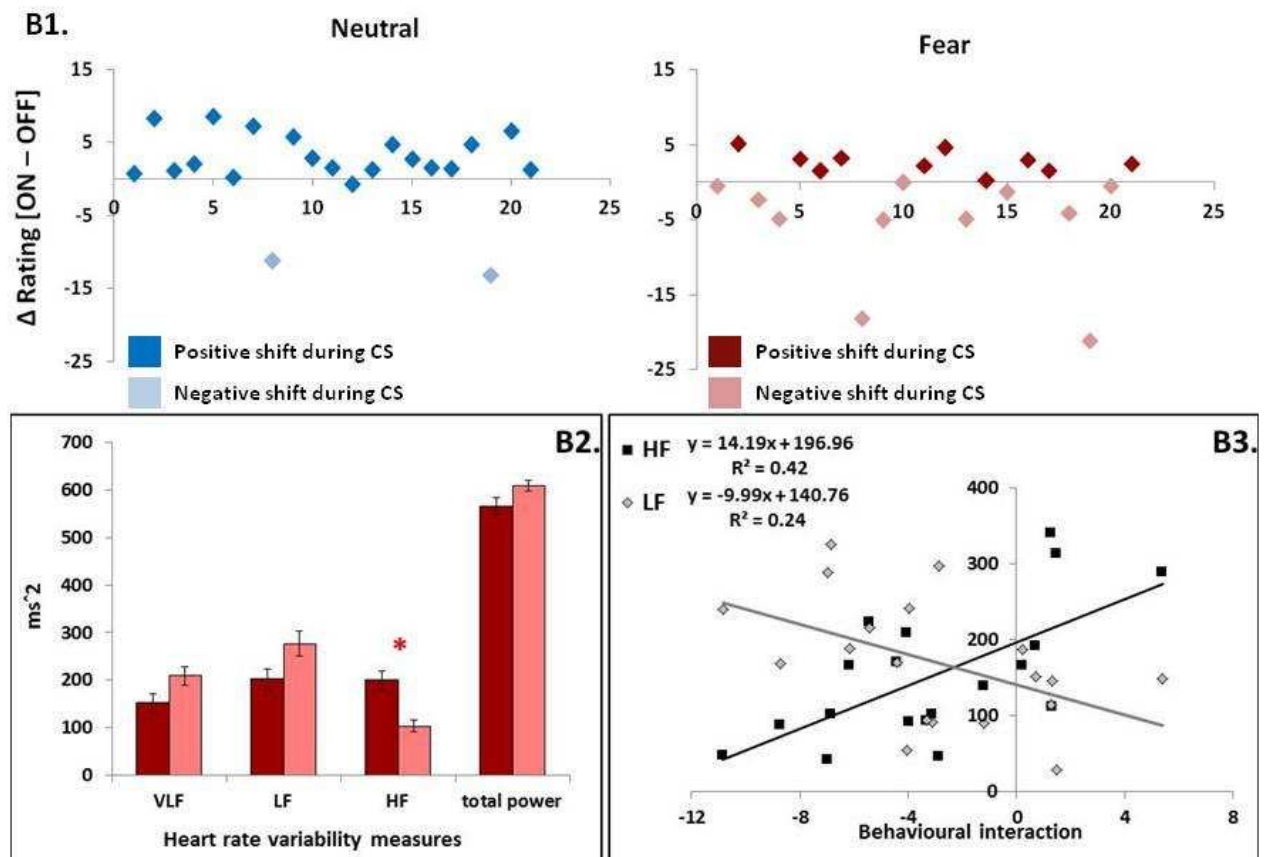
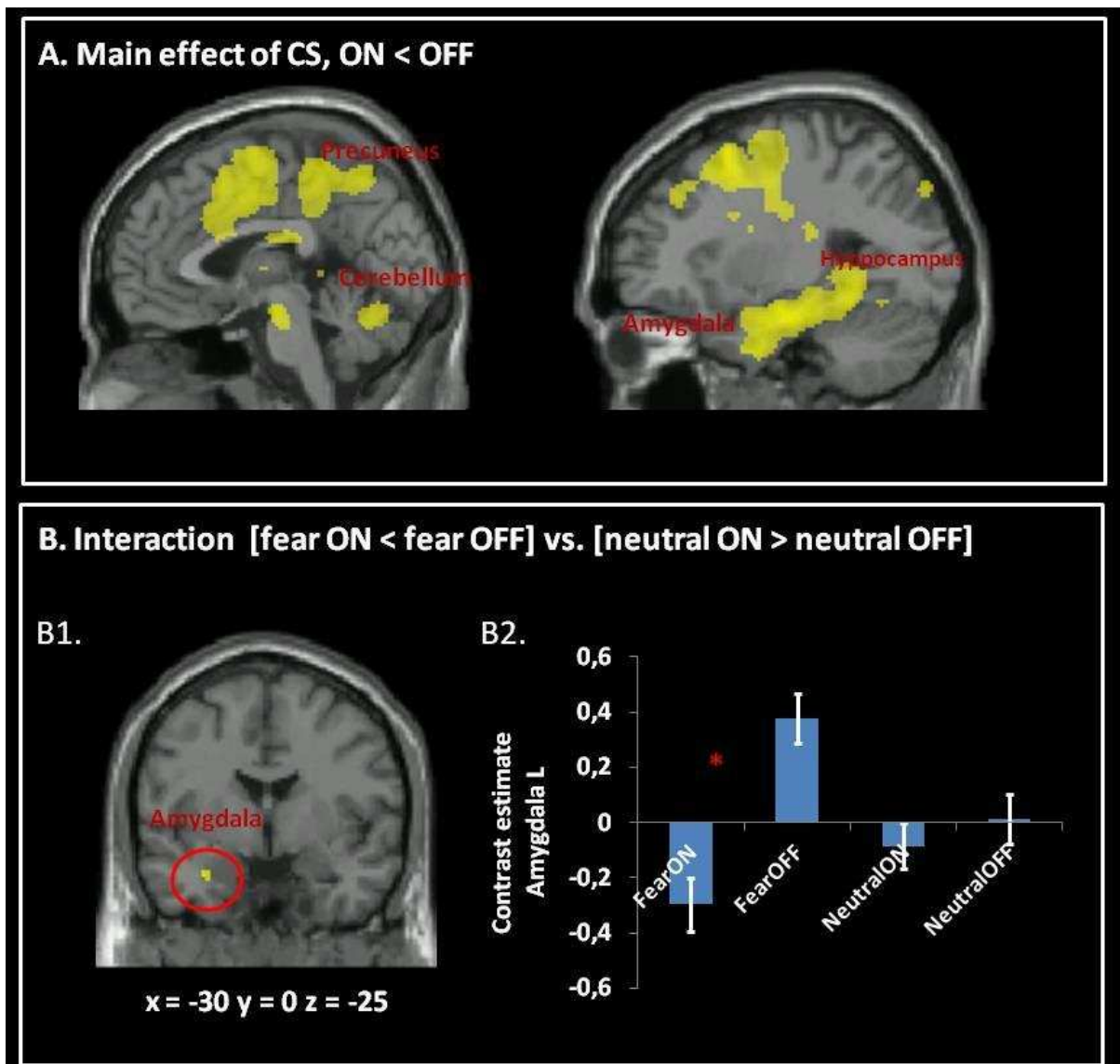
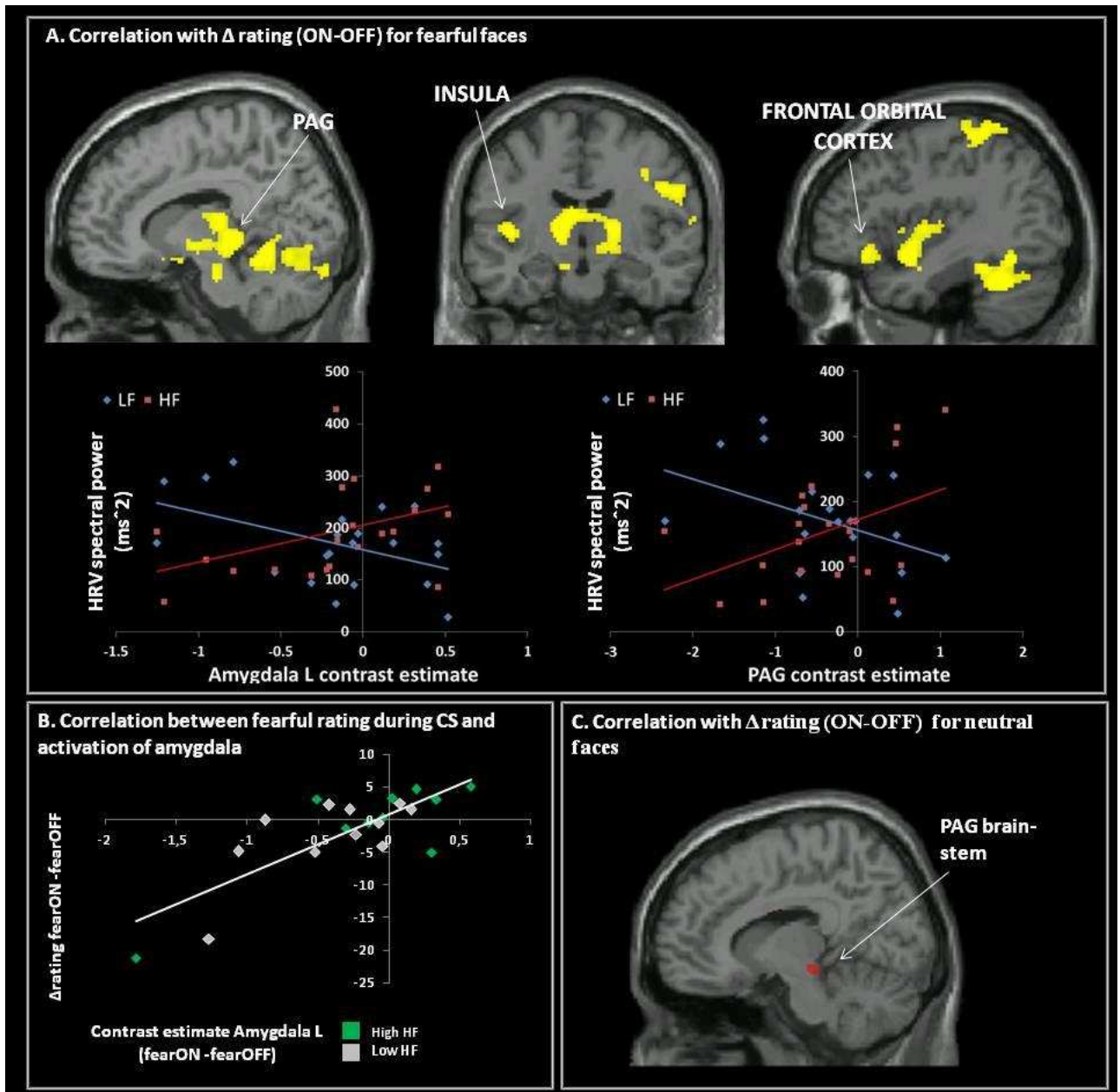


Figure 2.

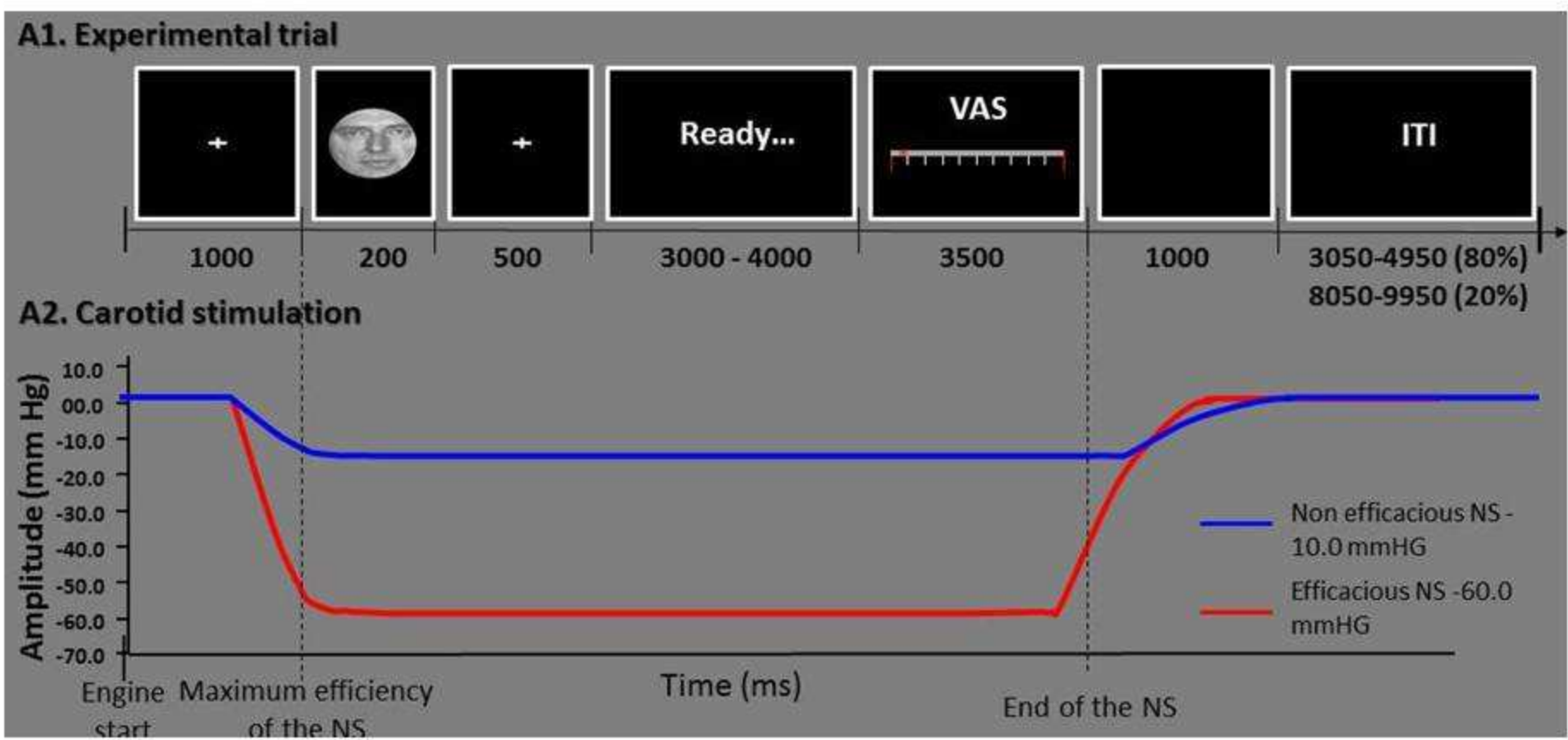


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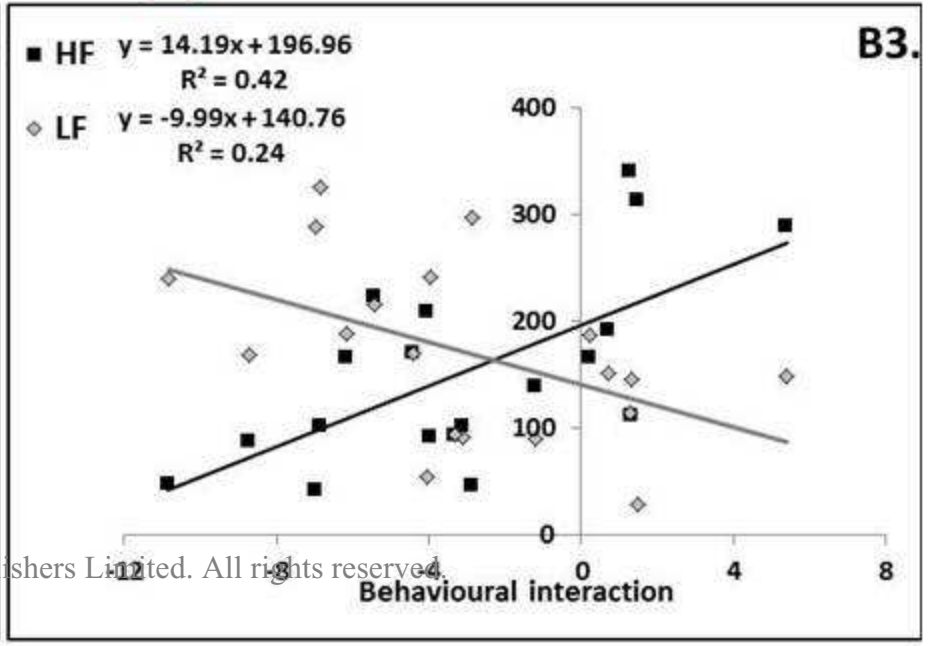
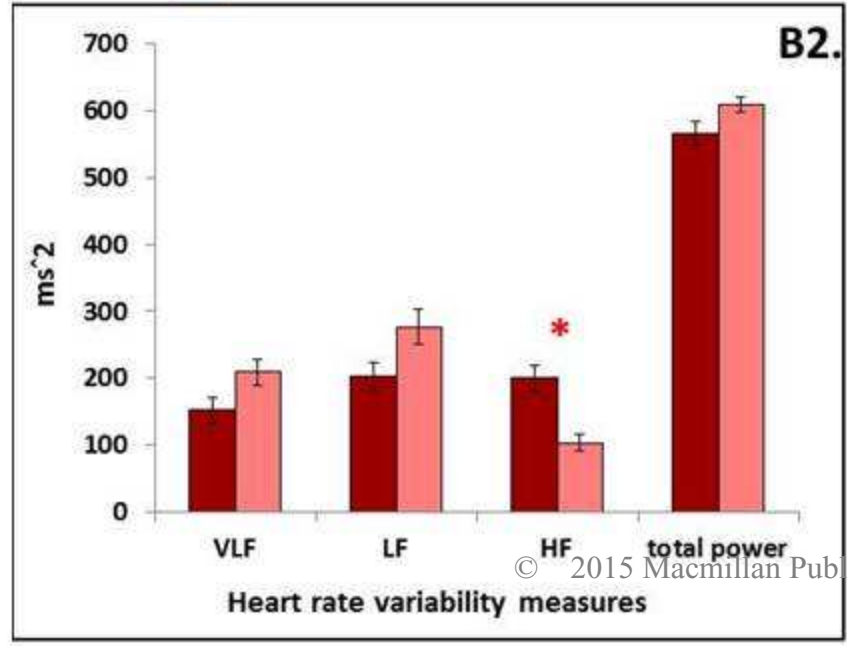
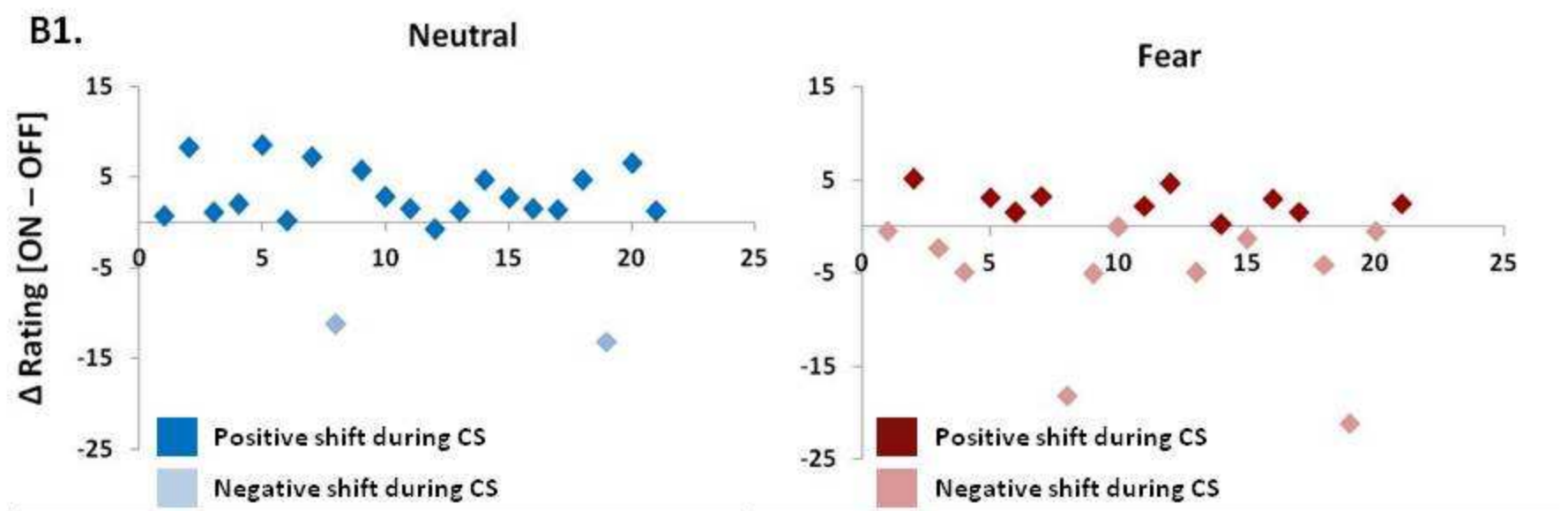
Figure 3.



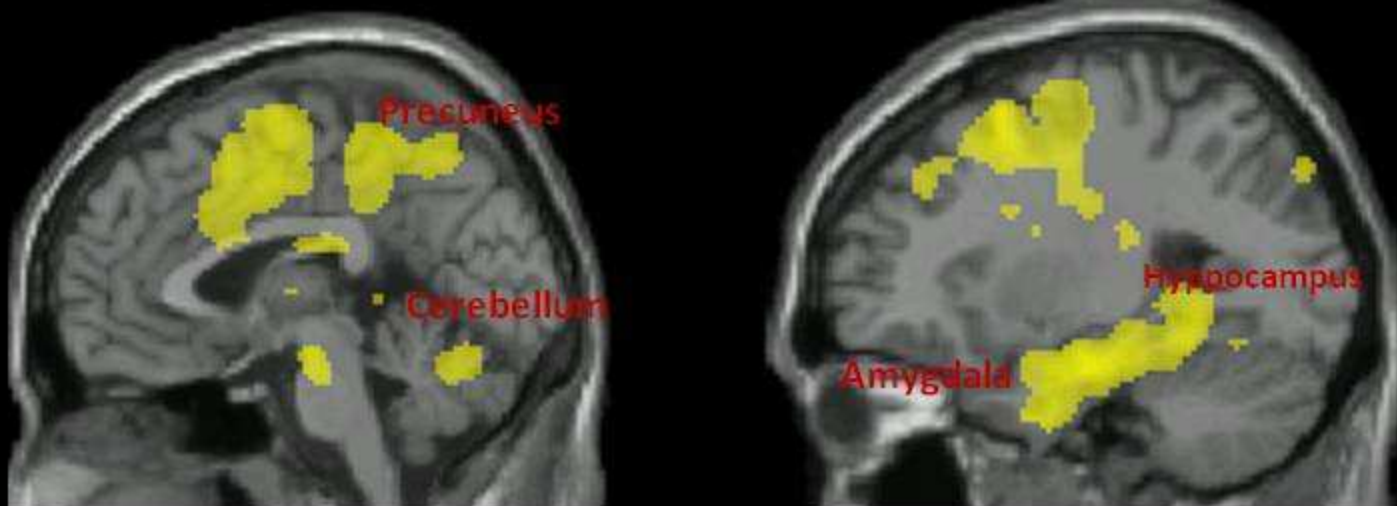
A. Emotional intensity paradigm



B. Behavioural results

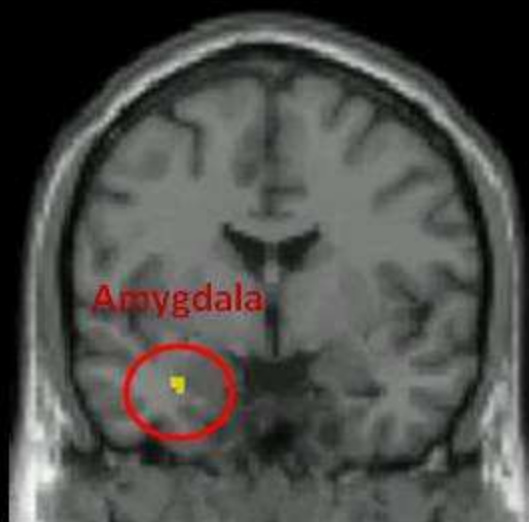


A. Main effect of CS, ON < OFF



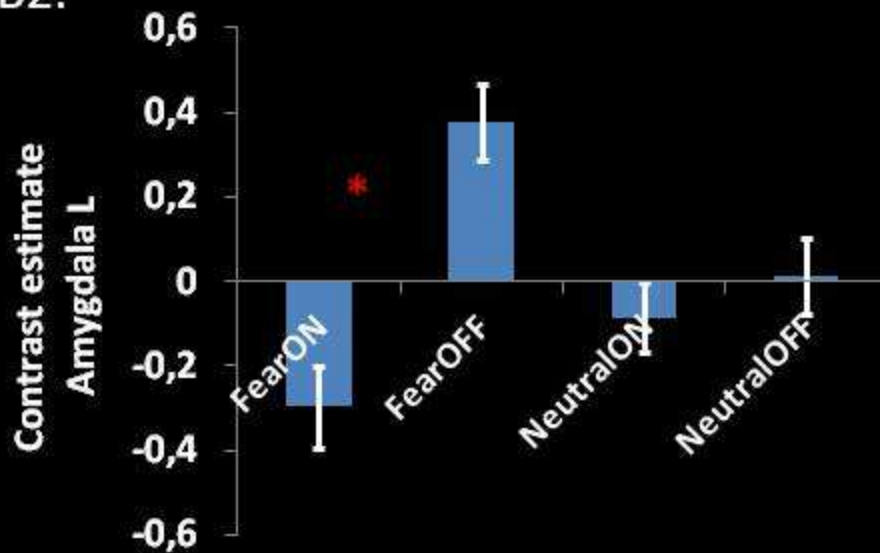
B. Interaction [fear ON < fear OFF] vs. [neutral ON > neutral OFF]

B1.

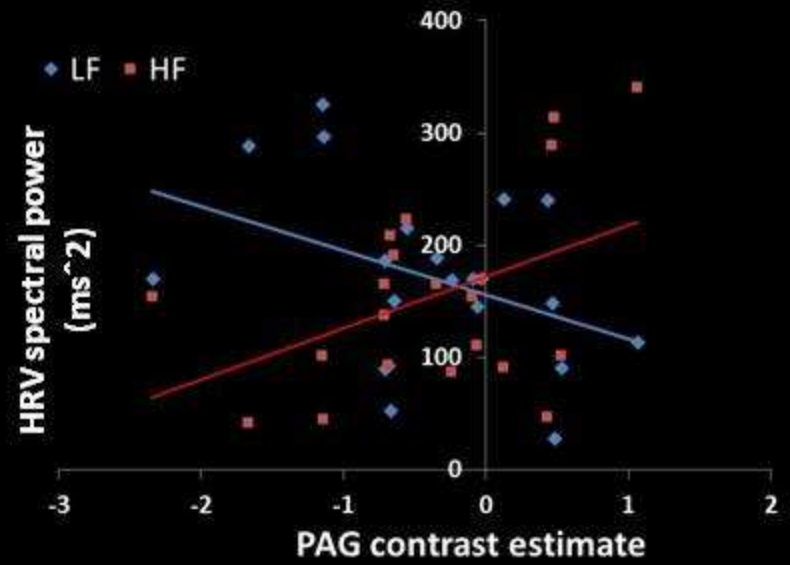
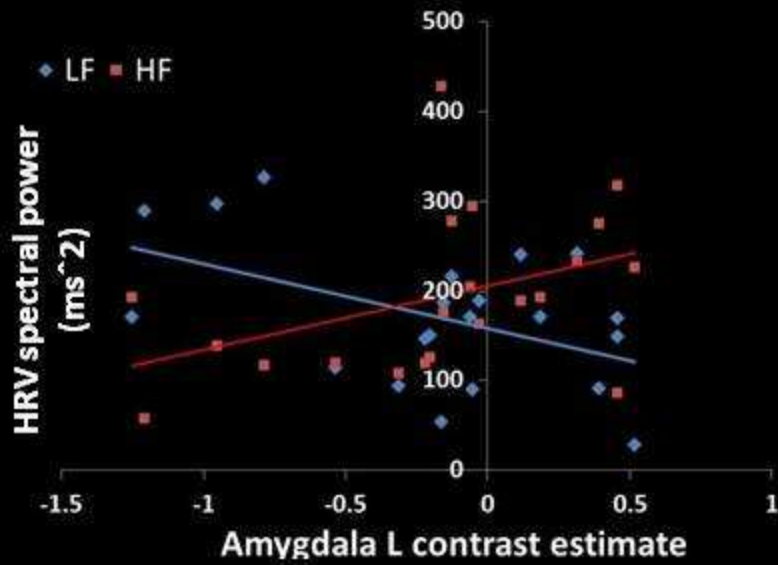
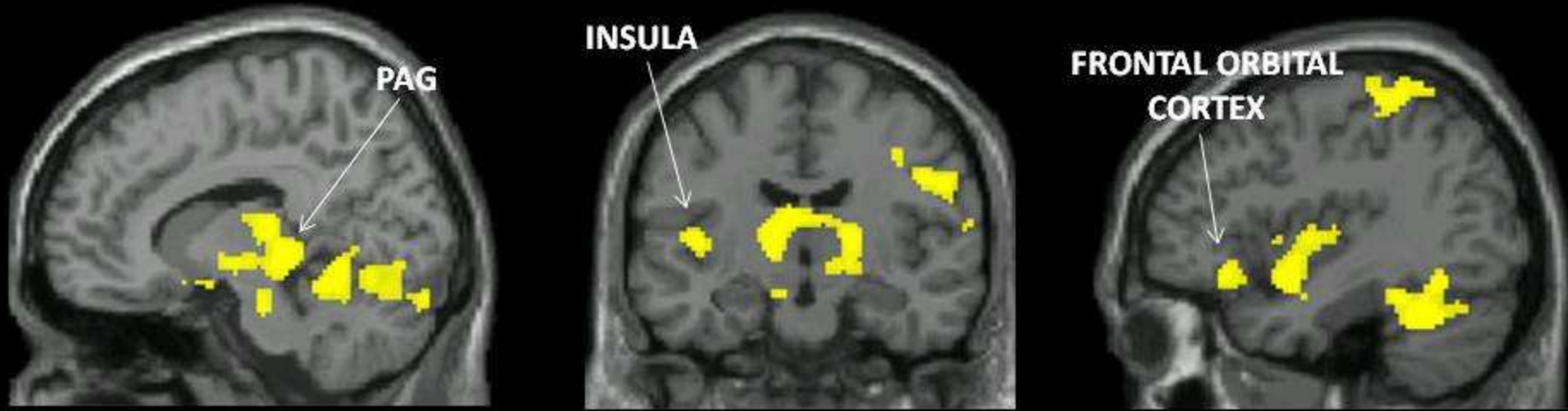


x = -30 y = 0 z = -25

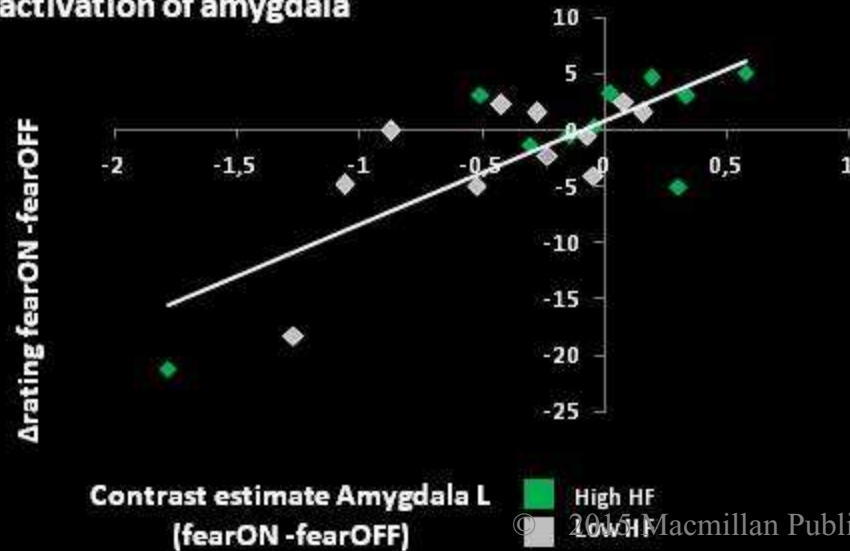
B2.



A. Correlation with Δ rating (ON-OFF) for fearful faces



B. Correlation between fearful rating during CS and activation of amygdala



C. Correlation with Δ rating (ON-OFF) for neutral faces

