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Eigenvector Centrality Mapping of sustained emotion

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Abstract

Due to methodological constraints, functional neuroimaging in affective neuroscience has focused on brief emotional episodes. This fMRI study computed Eigenvector Centrality Mapping (identifying computational hubs within networks of inter-connected structures) and Functional Connectivity (FC) analysis to reveal neural networks underlying sustained emotions. Sustained emotions were evoked using joyful or fearful music, presented in four minute trials. Results show that superficial amygdala (SF), laterobasal amygdala (LB), hypothalamus, and striatum function as computational hubs during sustained joy. SF showed FC during joy with the nucleus accumbens (Nac), suggesting that SF and Nac modulate approach-avoidance behavior in response to social cues such as music. The striatum exhibited FC during joy with premotor cortex, areas 1 and 7a, hippocampus, insula and cingulate cortex, showing that sensorimotor, attentional, and emotional processes converge in the striatum during music perception. The hypothalamus showed FC during joy with hippocampus and medio-dorsal thalamus, suggesting that hypothalamic endocrine activity is modulated by hippocampal and thalamic activity during sustained periods of music-evoked emotion. This fMRI study is the first to reveal a functional architecture of sustained emotion, indicating that emotions measured on a scale of minutes involve different neural correlates than those measured on a scale of seconds.

Keywords: sustained emotion; fMRI; eigenvector centrality mapping; music; superficial amygdala; laterobasal amygdala; hypothalamus; striatum; nucleus accumbens

Introduction

The majority of research in affective neuroscience has focussed on initial reactions to external or internal stimuli. While this is an ecologically valid approach for emotions such as surprise, or recognition of emotional expressions, the majority of emotions experienced by humans in everyday life usually span over longer time periods, in the range of minutes or even longer (e.g., joy, worry, fear, or sadness). Although only few functional neuroimaging studies are available on this topic, several lines of evidence indicate that neural activity underlying emotion changes over time: Firstly, it appears that activity levels in limbic/paralimbic structures change significantly over time, which might be related, at least in part, to different functional connections between brain structures constituting a network underlying that emotion. For example, combining PET and fMRI data, Salimpoor et al. (2011) showed that during the anticipation of a music-evoked frisson (involving exceptionally strong feelings of pleasantness and reward) dopamine availability increased in the dorsal striatum, whereas during the experience of the frisson itself, dopamine availability increased in the ventral striatum

(probably the nucleus accumbens). Consistent with this finding, an fMRI study with musical stimuli of 1 min duration showed that BOLD signal values in amygdala, ventral striatum, hippocampus, parahippocampal gyrus and temporal pole were significantly higher during the second half of each musical stimulus (seconds 30 to 60) compared to the first half (Koelsch et al., 2006). Secondly, while autonomic responses to emotional stimuli are relatively quick (within the range of seconds), endocrine changes are considerably slower (usually within the range of minutes, or even longer, see e.g. Gotthardt et al., 1995). Therefore, neural activity initiating and monitoring such endocrine processes might go unnoticed when investigating initial reactions to stimuli only. That is, neural correlates of emotional experiences that usually last longer than just a few seconds can change over time, and there is lack of knowledge regarding neural correlates of emotional states that last several minutes. The present study investigates this issue, thus exploring a blind spot in the current view on neural correlates of emotion.

Investigating neural correlates of emotional states that span longer time intervals (such as minutes) using fMRI is challenging because traditional analysis methods require modelling of the hemodynamic response function. To achieve a reasonable statistical power, this requires a sufficient number of trials per experimental condition (usually at least about 20), and thus relatively short stimuli. For example, previous fMRI experiments with musical stimuli used stimulus durations between 12 and 24 s (Eldar et al., 2007; Menon and Levitin, 2005; Ball et al., 2007), or 44 s up to maximally 1 min (Baumgartner et al., 2006; Trost et al., 2012; Koelsch et al., 2006; Mitterschiffthaler et al., 2007). Functional neuroimaging studies using films (Hasson et al., 2004; Goldin et al., 2005) or a story (Wallentin et al., 2011) have used longer stimuli (up to 30 min, see Hasson et al., 2004), but to achieve a high statistical power these studies used continuous emotion regressors (Goldin et al., 2005), or continuous inter-subject correlations (Hasson et al., 2004), which inform us about neural correlates of changing emotional experience, rather than about sustained emotional states. It should be mentioned that, in contrast to fMRI, PET studies typically use longer time intervals to evoke and measure emotion, often around 60 s or longer (for a review of PET studies on emotion see, e.g., Costafreda et al., 2008). However, regarding functional connectivity, or similar analyses involving correlational computations between voxels of the time-series of a scanning session, fMRI can be more informative than PET due to fMRI's higher spatial and temporal resolution (Poeppel et al., 2008).

To overcome the methodological barrier constraining the duration of experimental stimuli used in fMRI research, we used a new data-driven and model-free approach, the Eigenvector Centrality Mapping (ECM, Lohmann et al., 2010). ECM attributes a centrality value to each voxel in the brain such that a voxel receives a large value if it is strongly correlated with many other nodes that are themselves central within the network (Google's Page-Rank algorithm is a variant of eigenvector centrality). ECM thus exploits small-world properties of the human brain (Sporns and Honey, 2006), and indicates the "computational hubs" of neural networks distributed across different macroscopic brain structures (Tomasi and Volkow, 2011). Because ECM is based on correlations between time series, it can be applied for time series as long as several minutes (with the upper limit being the maximal length of a scanning session). For example, a previous study with a within-subjects design compared data of 7.6-minutes resting state scans of subjects when they were in states of hunger or satiety (Lohmann et al., 2010, that study reported that centrality values were higher during the

hungry state in the posterior cingulate cortex and the precuneus,). ECM is thus reminiscent of resting-state fMRI, except that ECM can also be computed for separate experimental conditions (i.e., not necessarily on resting state data), such as different emotion conditions. Hence, ECM can be used to identify emotion-specific computational hubs, beyond the computational hubs involved in resting state activity.

In the present study, we used for the first time ECM to investigate neural correlates of emotion. We employed three experimental conditions in which musical stimuli evoked either joy, or fear, or neither joy nor fear ("neutral" condition). Each condition consisted of one single trial of 4 min duration (Figure 1). That is, there were three trials per participant, each with a duration of four minutes: one joy, one fear, and one neutral trial (ordering of trials was counterbalanced across subjects). Computational hubs identified in the contrasts between conditions were then used as seed regions for functional connectivity (FC) analysis. FC was computed separately for each condition, and FC maps were compared between conditions to identify emotion-specific functional connections between the identified ECM hubs and other brain structures.

This enabled us to investigate brain networks underlying joy and fear on the time-scale of minutes. Previous studies implicated the amygdala, in particular the lateral and basolateral nuclei, in the evaluation of both positive and negative stimuli (LeDoux, 2000; Paton et al., 2006; Murray, 2007; Holland and Gallagher, 2004), and the central amygdala in initiating behavioural, autonomic, and endocrine responses to such stimuli (LeDoux, 2000). These studies investigated phasic emotional responses – whether the amygdala also plays a role for tonic emotions has remained unknown. Therefore, we aimed at testing whether the direct contrast of ECMs between the joy and the fear condition in our study (calculated for several minutes of emotional experience) would show differences in these structures. In addition, we expected differences between conditions in neural structures involved in endocrine changes, specifically hypothalamus and hippocampus (which has dense bidirectional connections with the hypothalamus, and is substantially involved in the modulation of hypothalamic endocrine activity, O'Mara, 2005).

Materials and Methods

Participants.

20 individuals (aged 21 – 38 years, $M = 25.55$, $SD = 4.80$, 10 females) took part in the experiment (for details see Supplementary Methods). Participants had normal hearing (as assessed with standard pure tone audiometry) and were right-handed (according to self-report). None of the participants was a professional musician or a music student. Exclusion criteria were past diagnosis of a neurological or psychiatric disorder, a score on Beck's Depression Inventory (Beck et al., 1993) of ≥ 13, excessive consumption of alcohol or caffeine during the 24 hours prior to testing, and poor sleep during the previous night. All subjects gave written informed consent, the study was conducted according to the Declaration of Helsinki and approved by the ethics committee of the School of Life Sciences and the Psychology Department of the University of Sussex.

Stimuli.

Musical stimuli were selected to evoke (a) joy (CD-recorded pieces of joyful music from various epochs and styles), (b) fear (excerpts from soundtracks of suspense movies and video games), or (c) neither joy nor fear (henceforth referred to as neutral stimuli). None of the stimuli contained vocals. Details about the stimuli are provided in the Supplementary Materials and Supplementary Table S1. There were $n = 8$ stimuli per category, each with a duration of 30 s, concatenated into musically versatile stimulus blocks of 4 min duration per category (see Figure 1). Importantly, joy, fear, and neutral stimuli were balanced across experimental conditions with regard to tempo (beats per minute), mean F0 pitch, F0 pitch range, F0 pitch variation, pitch centroid values, spectral complexity, and spectral flux. A detailed acoustic analysis of the stimuli is provided in the Supplementary Materials. In brief, 177 acoustical descriptors were extracted and compared between conditions (joy, neutral, fear) using one-way ANOVAs. Significant effects of condition were indicated for ten acoustical factors (mean and variance of F0 salience, mean and variance of sensory dissonance, mean chord strength, mean key strength, mean and variance of spectral flux, mean spectral crest, and mean spectral complexity). To compensate for these acoustical differences, the values of these psychoacoustic parameters were used in the fMRI data analysis as regressors of no interest (see *Data Analysis* for details).

Procedure.

Each participant listened to three different blocks, or trials, of musical stimuli (each trial lasting 4 min): One joy trial, one fear trial, and one neutral trial (see Figure 1). Ordering of trials was counterbalanced across subjects.

Participants were asked to listen to the musical stimuli with their eyes closed. Each block of musical stimuli was followed by an interval of 2 s in which a sine-wave tone of 350 Hz and 1 s duration signaled participants to open their eyes and to commence the rating procedure. During the rating procedure, participants indicated how they felt at the end of each trial with regard to *valence* (pleasantness), *arousal*, *joy*, and *fear*. That is, participants provided ratings about how they actually felt, and not about which emotion they thought each block of stimuli was supposed to express (Gabrielson and Juslin, 2003). Ratings were obtained with 6-point Likert scales (ranging from "not at all" to "very much"). The time interval for the rating procedure was 16 s. The total length of the fMRI experiment thus amounted to about 14 min. Musical stimuli were presented using Presentation (version 13.0, Neurobehavioral systems, Albany, CA, USA) via MRI compatible headphones (under which participants wore earplugs). Instructions and rating screens were delivered through MRI compatible liquid crystal display goggles (Resonance Technology Inc., Northridge, CA, USA).

MR Scanning.

Scanning was performed with a 3T Siemens Magnetom TrioTim. Prior to the functional MR measurements, a high-resolution (1x1x1 mm) T1-weighted anatomical reference image was acquired from each participant using a rapid acquisition gradient echo (MP-RAGE) sequence. Continuous Echo

Planar Imaging (EPI) was used with a TE of 30 ms and a TR of 2,000 ms. Slice-acquisition was interleaved within the TR interval. The matrix acquired was 64x64 voxels with a Field Of View (FOV) of 192 mm, resulting in an in-plane resolution of 3 mm. Slice thickness was 3 mm with an interslice gap of 0.6 mm (37 slices, whole brain coverage). The acquisition window was tilted at an angle of 30 degrees relative to the AC-PC line in order to minimize susceptibility artifacts in the orbitofrontal cortex (Deichmann et al., 2002, 2003; Weiskopf et al., 2007). Given the analyses methods employed, a continuous scanning design was preferable for optimum correlation estimations (see *Data Analysis* for details).

Data Analysis.

FMRI data were processed using LIPSIA 2.1 (Lohmann et al., 2001). Data were corrected for slicetime acquisition and normalized into MNI-space-registered images with isotropic voxels of 3 cubic millimeters. A temporal highpass filter with a cutoff frequency of 1/90 Hz was applied to remove low frequency drifts in the fMRI time series, and a spatial smoothing was performed using a 3D Gaussian kernel and a filter size of 6 mm FWHM.

The mean signal value per scan was computed and regressed out of each participant's data. Similarly, the movement parameters of each participant were regressed out of the entire fMRI timeseries acquired. In addition, the psychoacoustic parameters that had been identified to differ significantly between experimental conditions (see Supplemental Materials for details) were regressed out of each respective experimental condition. Thus, variance that could be explained by any of these factors was removed from the fMRI timeseries.

Functional MR data were analyzed using *Eigenvector Centrality Mapping* (ECM, Lohmann et al., 2010). On the first-level of statistical estimations, whole-brain ECM was computed separately for each participant, and separately for each trial (i.e., separately for the 4 minute block of each condition). On the second level of the ECM analysis, ECMs were compared between experimental conditions using voxel-wise paired sample $t-$tests. Results were corrected for multiple comparisons by the use of cluster-size and cluster-value thresholds obtained by Monte Carlo simulations with a significance level of $p < 0.05$ (Lohmann et al., 2008).

The ECM clusters identified by these analyses were then used as seeds for *functional connectivity analyses*: Each significant cluster identified by the ECM analysis was used as a functional connectivity seed, by computing the amount of correlation of the average timecourse of activity within each cluster with the activity in all other voxels. Functional connectivity maps were calculated separately for each experimental condition and for each participant, and then normalized across subjects. Subsequently, the normalized maps were compared between experimental conditions using paired $t-$tests corrected for multiple comparisons by the use of cluster-size and cluster-value thresholds obtained by Monte Carlo simulations with a significance level of $p < 0.05$ (Lohmann et al., 2008).

Results

Behavioral Data

Behavioral data are summarized in Table 1 and Figure 2. *Joy ratings* were higher for joy than neutral stimuli ($t(19) = 4.92, p < 0.0001$), and tended to be higher for neutral than fear stimuli ($t(19) = 2.55, p < 0.05$). *Fear ratings* were higher for fear than joy stimuli ($t(19) = 5.75, p < 0.0001$), but did not differ between fear and neutral stimuli ($p > .7$). *Valence (pleasantness) ratings* were higher for joy than neutral stimuli ($t(19) = 4.30, p < 0.001$), and higher for joy than fear stimuli ($t(19) = 6.79, p < 0.0001$), but did not differ significantly between neutral and fear stimuli ($p = .59$). *Arousal ratings* did not differ between joy and fear stimuli ($p = 1$), but tended to be higher for joy than neutral stimuli ($t(19) = 2.11, p < 0.05$), and higher for fear than neutral stimuli ($t(19) = 2.45, p < 0.05$).

fMRI data

Eigenvector centrality maps (ECMs) were computed separately for each emotion condition, and compared between conditions using voxel-wise $t-$tests (corrected for multiple comparisons, $p < .05$, see *Materials and Methods* for details). Results of these tests are listed in Table 2 and shown in Figure 3a. The contrast *joy* > *fear* showed significantly higher centrality values during joy (compared to fear) in the left superficial (SF) amygdala (extending into the hippocampal-amygdaloid transition area) and the right laterobasal (LB) group of the amygdala (extending into the superficial group of the amygdala). In the left hemisphere, a cluster of significantly activated voxels protracted from the striatum (putamen and caudate nucleus) into the claustrum and the piriform cortex. Morever, significant ECM clusters were observed in the hypothalamus bilaterally. The opposite contrast (*fear* > *joy*) did not reveal any significantly activated clusters. Note that values of acoustic descriptors that differed between conditions were introduced as regressors of no interest during the pre-processing (see *Data Analysis* for details). Therefore, it is unlikely that acoustical differences between stimuli contributed to the present results.

Comparisons with the neutral condition showed that, in the left SF as well as in the hypothalamus, centrality values were significantly higher for joy than for neutral ($p < .05$ for each structure, corrected for multiple comparisons), and nominally (but not significantly) lower in the fear compared to the neutral condition. In the right LB, centrality values were nominally higher for joy than for neutral, and higher for neutral than for fear stimuli, but these differences were statistically not significant. In the striatum, centrality values tended to be higher for joy than for neutral ($z = 3.01$), and were nominally higher for neutral than for fear, but none of these differences was statistically significant when corrected for multiple comparisons.

Functional Connectivity analysis. The ECM clusters were then used as seed regions for functional connectivity analysis, and functional connectivity maps were compared between experimental conditions (that is, for each ECM cluster, the average timecourse of activity was used as seed time-series in functional connectivity analyses to identify target regions for which the covariation of activity be-

tween seed and target regions was significantly different between experimental conditions, see *Data Analysis* for details). Results (corrected for multiple comparisons, $p < 0.05$) are listed in Table 3 and summarized in Figures 3b & 4).

The *left superficial amygdala* (SF) showed stronger functional connectivity during joy than during fear stimuli with the left medial thalamic region (MTR, the maximum was located in the paraventricular nucleus of the thalamus). The *right laterobasal amygdala* (LB) showed stronger functional connectivity during joy than during fear stimuli with the left central sulcus (area 3b according to Geyer et al., 1999) and with primary visual cortex (area 17). The *hypothalamus* showed stronger functional connectivity during joy than during fear stimuli with the left hippocampus, the right thalamus, V1, V3v, and the cerebellum. Finally, the *left striatum* exhibited significantly stronger functional connectivity during joy than during fear stimuli with left LB, both left and right hippocampus, left anterior perforated substance, right circular insular sulcus, posterior midcingulate cortex (area p24b' according to Palomero-Gallagher et al., 2009), supplementary motor area (SMA), postcentral gyrus (area 1), the medial bank of the left intraparietal sulcus (IPS, area hIP3 according to Scheperjans et al., 2008), left lateral superior parietal lobule (area 7A according to Scheperjans et al., 2008), and posterior cingulate cortex (area v23 according to Palomero-Gallagher et al., 2009). None of the comparisons showed stronger functional connectivity during fear (compared to joy).

Discussion

Our data reveal a neural network underlying sustained positive emotion with the (left) superficial group of the amygdala (SF), the (right) laterobasal group of the amygdala (LB), hypothalamus, and the striatum as computational hubs, as well as a number of functionally connected cortical and subcortical structures (summarized in Figure 4). These structures include hippocampus, medial thalamus, cerebellum, and neocortical structures involved in attention, sensorimotor processes and vision. Out of these structures, thalamus, hippocampus, and (primary) visual cortex were functionally connected to more than one computational hub, thus constituting second-order computational hubs.

The involvement of SF (consisting of anterior amygdaloid area, amygdalopyriform transition area, cortical nuclei, and amygdaloid-hippocampal area according, e.g., to Amunts et al., 2005) indicates that SF plays a central role during sustained periods of emotional experience. Hence, other than previously believed, SF is not only active during the initial stages of stimulus evaluation. Our data corroborate the notion that SF is involved in the evaluation of signals with social relevance (Bzdok et al., 2012), and indicate that SF is particularly sensitive for positive social signals, including joy expressed by music: On the one hand, SF is sensitive to social stimuli, as indicated by an fMRI study by Goossens et al. (2009) in which signal changes in the SF were observed in response to faces, but not to houses. On the other hand, trustworthiness as well as attractiveness judgments of faces overlap in the SF (Bzdok et al., 2011). It has previously been argued that individuals perceive music as a stimulus with social significance due to its communicative properties (Cross and Morley, 2008; Steinbeis and Koelsch, 2008; Koelsch, 2010), and the finding that SF exhibits stronger activity in

response to joy than fear (and neutral) stimuli indicates that neural activity in SF also codes whether social signals are incentive or aversive.

The SF showed functional connectivity with the medial thalamic region (MTR) which was specific for joy. Both amygdala and thalamus possess evaluative and mnemonic functions, and efferents to the MTR enable the amygdala to influence neural activity in large regions of the (prefrontal) cortex (Aggleton and Mishkin, 1984). In addition, both amygdala and MTR show high density of opiate receptors (Wamsley et al., 1982), and it is interesting to note that both SF and MTR (in particular the paraventricular nucleus of the thalamus) project to the nucleus accumbens (Nac) (Bzdok et al., 2012; Li and Kirouac, 2008). Such connections have been proposed to modulate approach-avoidance behavior towards social cues in human interaction (Bzdok et al., 2011), and based on the studies showing projections between SF and Nac (Bzdok et al., 2012; Li and Kirouac, 2008) we also investigated possible emotion-specific functional connectivity between SF (used as seed region) and Nac in our data, using a lower statistical threshold (uncorrected $z-$maps thresholded at $p < .001$ and a voxel-extent of five voxels). This revealed functional connectivity between SF and ventral striatum / Nac that was stronger during joy than during fear (see Supplemental Figure S1, see also dashed line in Figure 4). Taken together, these results indicate that, in humans, SF and Nac modulate approach-avoidance behavior in response to social cues, and that functional connectivity between SF, MTR and Nac is modulated by the emotional valence of stimuli.

The (right) laterobasal group of the amygdala (LB, consisting of lateral, basolateral, basomedial and paralaminar nuclei Amunts et al., 2005) also showed higher centrality values during joy. These data are the first to show that LB plays a central role for emotions lasting over the course of minutes. LB is conceived of as the main amygdalar input structure for auditory information (as well as for sensory information from other modalities), and involved in the evaluation and learning of both positive and negative stimuli (LeDoux, 2000; Critchley et al., 2002; Vuilleumier, 2005; Paton et al., 2006; Murray, 2007; Holland and Gallagher, 2004). Note that LB has been implicated in learning and encoding of stimuli signalling reward (Paton et al., 2006; Murray, 2007) and the generation of reward expectancies that guide goal-directed behavior (Holland and Gallagher, 2004). Thus, activation of LB in the present study was likely to be due to the coding of the reward value of pleasant music. Of particular interest is also the functional connectivity between LB and sensory cortex (probably area 3b). LB is connected to sensory areas (both directly and indirectly, Murray, 2007; Shi and Cassell, 1999), and this connection may well be related to sensory aspects, and thus to the subjective feeling component, of emotion (Harrison et al., 2010; Herwig et al., 2010; Gray et al., 2007).

The hypothalamus also showed higher centrality values during joy (compared to fear). This indicates that the hypothalamus is involved in joy, in particular during longer emotional periods. Activation of the hypothalamus in the present study was probably due to endocrine changes, and the fact that hypothalamic activation is rarely observed in fMRI studies on emotion is presumably due to the fact that such changes are relatively slow (and thus go unnoticed in experiments with shorter stimulus durations). Future endocrinological studies could aim at specifying hormones released during experiences of joy (studies on endocrine effects of music are reviewed in Koelsch and Stegemann, 2012).

Importantly, the hypothalamus showed emotion-specific functional connectivity (stronger for joy than for fear) with the subiculum of the hippocampal formation. This finding is well in accordance with the observations that the subiculum has dense bidirectional connections with the hypothalamus (O'Mara, 2005). These connections include projections from the subiculum to the medial preoptic area, the ventromedial and dorsomedial nuclei, and ventral premammillary as well as medial mammillary nuclei (O'Mara, 2005). The functional significance of these connections is thought to be modulation of hypothalamus-pituitary-andrenal (HPA) axis activity (in particular inhibition of HPA-axis activity mediated by GABAergic neurones, O'Mara, 2005). Thus, the subiculum is substantially involved in terminating or limiting HPA axis activity in response to stress. The present results hence indicate that the hippocampal formation plays a role for modulating hypothalamic endocrine activity during sustained periods of music-evoked positive emotion; this finding has important implications for the application of music therapy to reduce stress and stress responses in both clinical and non-clinical settings (reviewed in Koelsch and Stegemann, 2012).

The (left) striatum was identified as another computational hub (in the comparison joy $>$ fear). Notably, compared to SF, LB, and hypothalamus, the striatum showed by far the largest number of emotion-specific functional connections with other structures, including (left) LB and (left) anterior perforated substance, bilatera hippocampus, posterior middle cingulate cortex, right circular insular sulcus, supplementary motor area (SMA), area 1, medial bank of the left intraparietal sulcus (area hIP3), left lateral superior parietal lobule (area 7A), and posterior cingulate cortex (PCC, area v23). The observation of these extensive functional connections of the striatum with other cerebral structures is consistent with anatomical studies showing that the entire neocortex, including sensorimotor and parietal association cortex, sends fibres to both the caudate nucleus and the putamen (Nieuwenhuys et al., 2008). In addition, the basolateral nucleus of the amygdala (Russchen et al., 1985), hippocampus (Parent and Hazrati, 1995; Haber et al., 1990) as well as cingulate cortex (Parent and Hazrati, 1995; Haber et al., 1990) send projections to the ventral striatum including, but not limited to, the nucleus accumbens. Although sensorimotor, association, and limbic cortical areas project in a segregated manner onto three distinct striatal regions (referred to as associative, sensorimotor and limbic striatal territories, Parent and Hazrati, 1995), it is striking that the region identified as striatal computational hub in our study is located at the borders of all three of these territories (c.f. Parent and Hazrati, 1995). Hence, our data on emotion-specific functional connections of the striatum are in remarkable agreement with anatomical projections to the striatum, and indicate that such projections play a role for emotional processes.

Previous music and language research implicated the striatum mainly in motor-related processes (for an exception see Salimpoor et al., 2011). The role of the striatum for emotional processes has first been discussed by MacLean (1972), who proposed that the striatal complex is part of a storage mechanism for learned emotive behaviors, a notion that is corroborated by the the functional connections of the striatum with sensorimotor and limibic structures in the present study. MacLean (1972) also proposed that the striatal complex plays a role for behavior involving conspecific recognition and communication in the form of rudimentary, non-verbal signalling. Our results emphasize the significant role of the striatum for emotional processes, and show that the striatum functions as a

computational hub in which sensorimotor, attentional, and emotional processes converge during the perception of positive music.

Conclusions

The present fMRI study is the first using Eigenvector Centrality Mapping for the analysis of neural networks underlying emotion, and the first to reveal the functional neuroarchitecture of sustained emotion (evoked and measured over the course of several minutes). The data show that both superficial (SF) and laterobasal (LB) nuclear groups of the amygdala play a role throughout sustained periods of joy and are (other than previously believed) not only active during the initial stages of stimulus evaluation. Results corroborate the recent notion that SF is involved in the evaluation of signals with social relevance, and they indicate that SF is particularly sensitive for social signals with positive valence, such as joy expressed by music. The functional connectivity between SF and nucleus accumbens (Nac) probably modulates approach-avoidance behavior in response to social cues, whereas the functional connectivity between LB and sensory areas appears to be related to sensory aspects, and thus to the subjective feeling component, of emotion. Our data on sustained emotions also indicate emotion-specific functional connectivity between hypothalamus and hippocampus, which is likely to be due to the modulation of hypothalamus-pituitary-andrenal (HPA) axis activity (in particular inhibition of HPA-axis activity) during extended periods of emotional experience. Of the four observed computational hubs, the striatal complex had by far the largest number of emotion-specific functional connections to other structures. This highlights the role of the striatal complex in emotion, in particular with regard to emotive sensorimotor functions. Our results are important because they expand our knowledge on neural networks underlying sustained emotional experience.

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	Fear	Neutral	Joy
joy	2.67 (0.61)	3.40 (1.10)	4.85 (0.75)
fear	3.00 (0.84)	2.90 (0.85)	2.00 (0.73)
valence	2.90 (0.72)	3.05 (1.15)	4.56 (0.85)
arousal	3.95 (1.23)	3.35 (0.93)	3.95 (1.10)

Table 1: Descriptive statistics of behavioral data (for test statistics see main text). Scales ranged from 1 ("not at all") to 6 ("very much").

	MNI coord.	cluster size (mm^3)	$z-$value: max (mean)
l superficial amygdala (70%)	-20 -9 -12	432	2.83 (2.57)
r laterobasal amygdala (70%)	28 -2 -18	621	3.63 (2.88)
l hypothalamus	-4 -2 -13	351	3.08 (2.66)
r hypothalamus[1]	6 0 -11	–	3.08
l striatum	-26 11 -7	1242	3.79 (2.71)

[1] The cluster with the maximum peak voxel in the l hypothalamus had an additional local maximum in the r hypothalamus

Table 2: Results of the ECM contrast emotion (joy $>$ fear), corrected for multiple comparisons ($p < .05$). Percentages in brackets indicate anatomical probabilities according to the SPM Anatomy Toolbox (Eickhoff et al., 2005).

	MNI coord.	cluster size (mm^3)	$z-$value: max (mean)
(a) *l superficial amygdala*			
l thalamus	-6 -6 4	513	4.14 (3.38)
(b) *r laterobasal amygdala*			
l central sulcus	-39 -18 52	2403	4.95 (3.46)
l calcarine sulcus (area 17, 90%)	-6 -95 3	3483	3.94 (3.41)
(c) *hypothalamus*			
l hippocampus (SUB, 70%)	-26 -23 -14	459	3.69 (3.30)
r thalamus	12 -24 7	702	4.18 (3.40)
r calcarine sulcus (area 17, 100%)	12 -76 7	729	3.89 (3.32)
l lingual gyrus (V3v, 60%)	-12 -81 -11	5778	3.93 (3.31)
cerebellar vermis (lobule V)	6 -54 -2	648	4.57 (3.61)
(d) *l striatum*			
paracentral lobule / SMA (area 6, 70%)	-3 -21 52	999	4.32 (3.44)
posterior MCC[1]	3 -20 41	–	3.62
l SPL (area 7A, 80%)	-33 -69 64	756	4.29 (3.48)
l IPS, superior bank (hIP3, 30%)	-39 -39 49	1809	3.83 (3.30)
l posterior IPS	-33 -69 31	1593	4.89 (3.48)
l precuneus	-3 -57 16	405	3.55 (3.26)
r postcentral gyrus (area 1, 70%)	45 -30 58	2106	5.88 (3.73)
l anterior perforated substance	-21 -15 -5	648	3.99 (3.43)
l hippocampus (CA, 70%)	-33 -18 -14	459	4.34 (3.53)
l LB[2] (LB, 100%)	-23 -6 -24	–	3.70
r hippocampus (CA, 90%)	29 -16 -15	459	4.34 (3.53)
r circular insular sulcus	42 -6 -11	1485	4.60 (3.61)

[1] The cluster with the maximum peak voxel in the paracentral lobule had an additional local maximum in the r posterior MCC

[2] The cluster with the maximum peak voxel in l hippocampus had an additional local maximum in the l LB

Table 3: Results of the emotion-specific functional connectivity analyses (contrast: joy > fear), corrected for multiple comparisons ($p < .05$). Seed-voxels used for the functional connectivity analyses are the peak voxels of the ECM results (ECM contrast joy > fear; seed regions are indicated by italic font in the outermost left column). For example, the superficial amygdala (which showed higher centrality values during joy compared to fear) showed increased functional connectivity with the thalamus during joy (compared to fear). Percentages in brackets indicate anatomical probabilities according to the SPM Anatomy Toolbox (Eickhoff et al., 2005). Abbreviations: CA: cornu ammonis of hippocampal formation; IPS: intraparietal sulcus; LB: laterobasal group of amygdala; MCC: midcingulate cortex; SF: superficial group of amygdala; SMA: supplementary motor area; SPL: superior parietal lobule; SUB: subiculum of hippocampal formation; l: left; r: right.

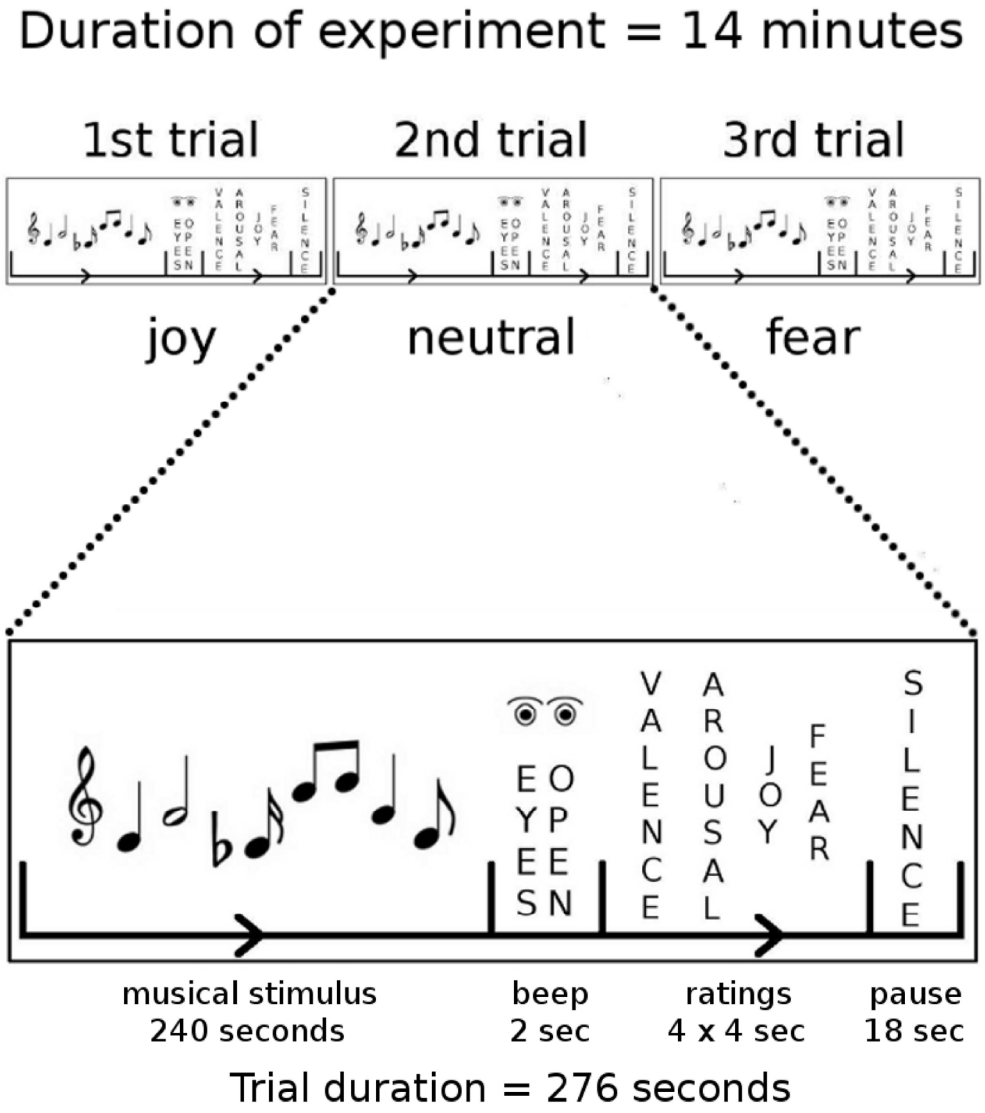
FIGURE LEGENDS

Figure 1. Experimental design. Three trials, each with a duration of several minutes, were presented to each subject. Each trial consisted of a music stimulus that was presented for 4 minutes (either joy, fear, or neutral, ordering was counterbalanced across subjects). Participants listened to the music with their eyes closed. The presentation of music was followed by a beep tone signalling to open the eyes and to commence the rating procedure. Four ratings (felt valence, arousal, joy, and fear) were obtained in 16 s.

Figure 2. Behavioral ratings. Participants rated their emotional state on four scales: (a) valence, (b) arousal, (c) joy, and (d) fear. Average ratings are depicted separately for each stimulus category (fear, neutral, joy). Scales ranged from 1 ("not at all") to 6 ("very much"). Note that joy stimuli were rated as more pleasant than fear and neutral ones (valence/pleasantness ratings of fear and neutral did not differ from each other). Also note that arousal ratings of joy and fear stimuli did not differ from each other (and both joy and fear stimuli were rated as more arousing than neutral stimuli).

Figure 3. fMRI results. (a) shows the comparison of Eigenvector Centrality Maps (ECM) between joy and fear (joy $>$ fear). Clusters of significantly higher centrality values during joy than fear were indicated in the hypothalamus (HYP), left superficial amygdala (SF), right laterobasal amygdala (LB) and left striatum (STR). These four clusters were used as seed regions for functional connectivity analyses. The results of the comparison of functional connectivity maps between joy and fear (joy $>$ fear) are shown in **(b)**, separately for the four seed regions (left SF: outermost left, right BL: middle left column, hypothalamus: middle right column, left striatum: outermost right column). Scale for **(b)** is the same as for **(a)**. The left SF showed emotion-specific functional connectivity (stronger during joy than fear) with the hypothalamus. The right BL showed stronger functional connectivity during joy than fear with somatosensory cortex (area 3b) and primary visual cortex (V1, bottom image of left middle column). The hypothalamus showed emotion-specific functional connectivity with the hippocampal formation (arrows), thalamus and primary visual cortex (V1, bottom image of right middle column). The left striatum showed stronger functional connectivity during joy than fear in supplementary motor area, midcingulate cortex and posterior cingulate cortex (arrow-heads), hippocampal formation (arrow), and laterobasal amygdala (bottom image of outermost right column). Images are shown in neurological convention, all results are corrected for multiple comparisons ($p < .05$).

Figure 4. Summary of results. Blue rectangles indicate computational hubs (joy $>$ fear) as indicated by the ECM, lines indicate functional connections to other structures as indicated by the emotion-specific (joy $>$ fear) functional connectivity analysis. The dotted line connecting SF and Nac indicates that this result was yielded by the uncorrected z-map (see main text). Yellow boxes indicate structures that are functionally connected to more than one ECM hub. Cer: cerebellum: Hipp: hippocampal formation; HYP: hypothalamus; LB: laterobasal group of amygdala; MCC: middle cingulate cortex; Nac: nucleus accumbens; PCC: posterior cingulate cortex; SF: superficial group of amygdala; SMA: supplementary motor area; STR: striatum; Th: Thalamus.



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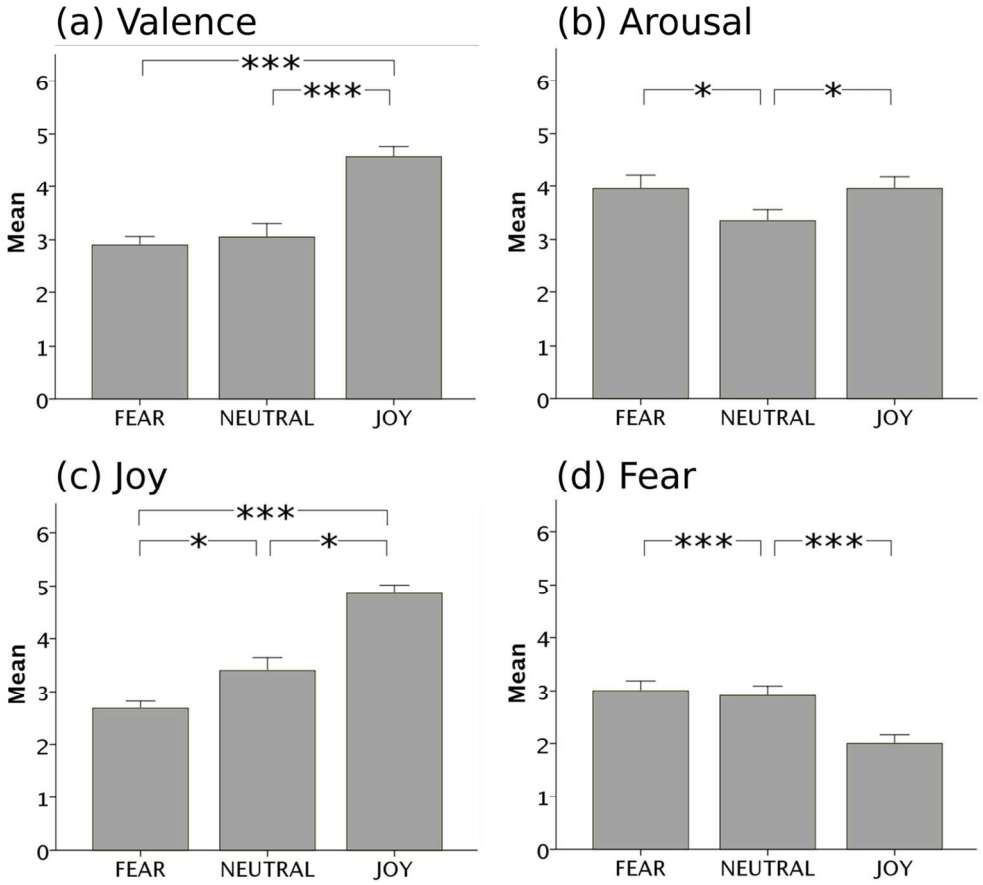

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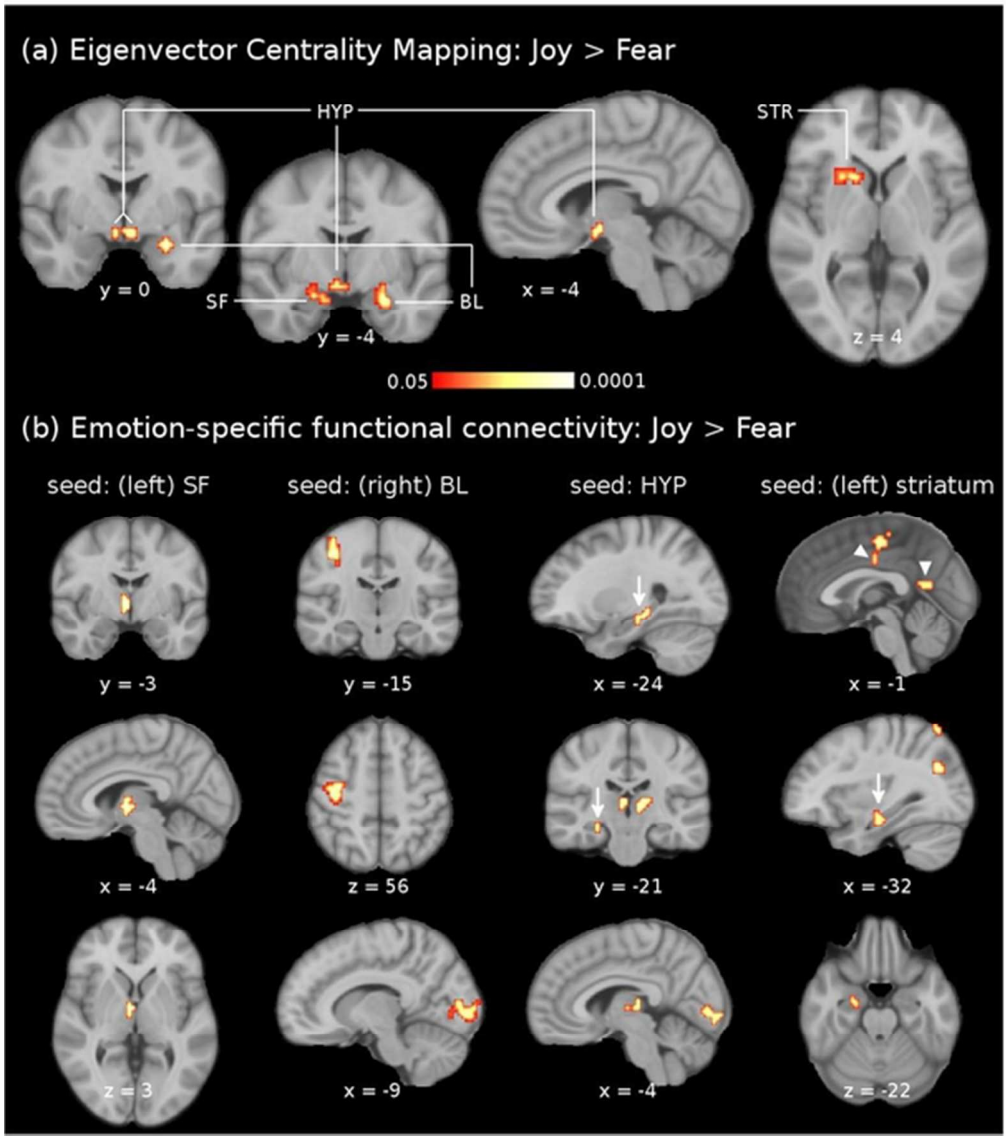

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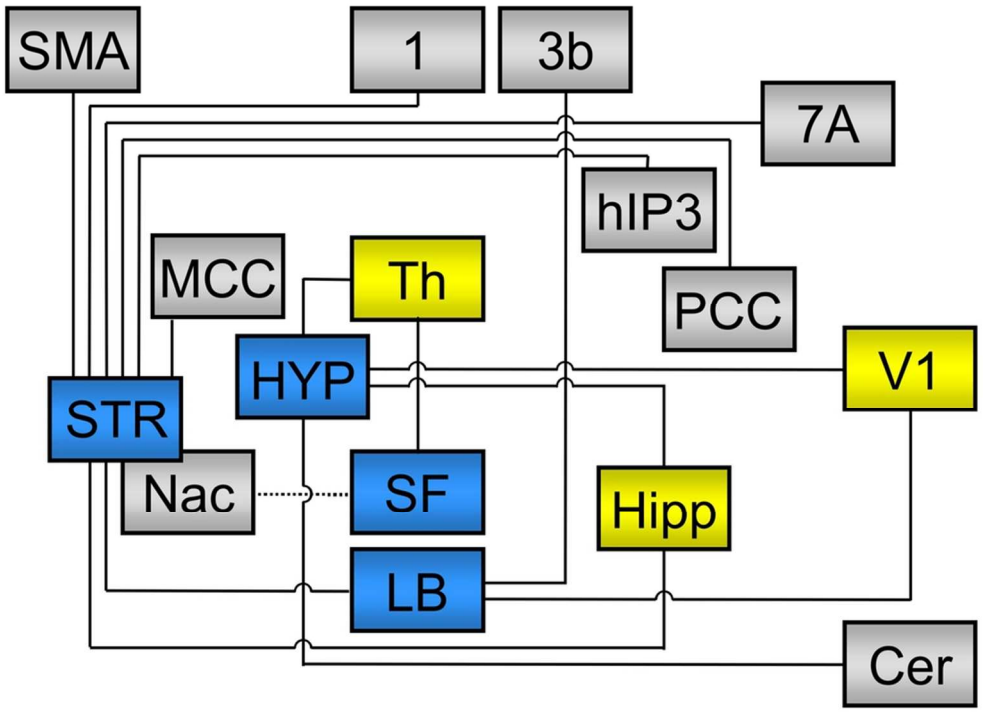

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88x64mm (300 x 300 DPI)