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Emotional responses to unpleasant music correlates with damage to the parahippocampal cortex

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Music is typically a pleasurable experience. But under certain circumstances, music can also be unpleasant, for example, when a young child randomly hits piano keys. Such unpleasant musical experiences have been shown to activate a network of brain structures involved in emotion, mostly located in the medial temporal lobe: the parahippocampal gyrus, amygdala, hippocampus and temporal pole. However, the differential roles of these regions remain largely unknown. In this study, pleasant and unpleasant music was presented to 17 patients with variable excisions of the medial temporal lobe, as well as to 19 matched controls. The pleasant music corresponded to happy and sad selections taken from the classical instrumental repertoire; the unpleasant music was the dissonant arrangement of the same selections. Only patients with substantial resections of the left or right parahippocampal cortex (PHC) gave highly abnormal judgements to dissonant music; they rated dissonant music as slightly pleasant while controls found it unpleasant. This indifference to dissonance was correlated with the remaining volume in the PHC, but was unrelated to the volume of the surrounding structures. The impairment was specific: the same patients judged consonant music to be pleasant, and were able to judge music as happy or sad. Furthermore, this lack of responsiveness to unpleasantness was not due to a perceptual disorder, because all patients were able to detect intentional errors in the musical excerpts. Moreover, the impairment differed from that induced by amygdala damage alone. These findings are consistent with a two-dimensional model of defensive responses to aversive stimuli, in which the PHC and the amygdala subserve different roles.

Keywords: emotions; epilepsy; dissonance; music; parahippocampal cortex

Abbreviations: PHC = parahippocampal cortex; PHG = parahippocampal gyrus; M.M. = metronome marking

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Introduction

Although musical preferences may vary across individuals, most ordinary listeners readily recognize that playing two adjacent keys on a keyboard, forming a minor second in musical terminology, constitutes unpleasant musical experiences. These musical experiences are elicited by dissonance. There is substantial evidence that dissonant music elicits unpleasant judgements in normal listeners (Plomp and Levelt, 1965; Wedin, 1972; Zentner and Kagan, 1996; 1998; Trainor and Heinmiller, 1998; Blood *et al.*, 1999; Costa *et al.*, 2000; Peretz *et al.*, 2001; Koelsch *et al.*, 2006). Dissonance also appears to be the most primitive musical feature to trigger emotional responses. Infants, even as young as 2-months-old, prefer consonant over dissonant music (Trainor *et al.*, 2002). Despite its well-known and reliable impact, the functional and neural correlates of emotional responses to dissonance remain largely unexplored. The goal of the present study was to contribute to the specification of its neural basis.

The perception of dissonance is a by product of the peripheral sensory organ, and results from the distortion created by the poor resolution power of the ear (von Helmholtz, 1885, 1954; Plomp and Levelt, 1965). Tones (or tone components) that are too close in pitch (e.g. a minor second) will create roughness when heard together because the human sensory system, at the level of the basilar membrane, does not have sufficient spatial resolution to separate the tones. Although this mechanical built-in account of dissonance is appealing, it cannot explain all forms of dissonance. In particular, this account of sensory dissonance fails to explain why successive pure tones, that are processed one at a time and thus can be normally resolved by the basilar membrane, are judged as unpleasant just as simultaneous sounds (e.g. Schellenberg and Trainor, 1996). Moreover, this account of sensory dissonance fails to explain how and why the poor resolution of the basilar membrane elicits negative emotions in listeners.

One possibility for this is that the principles underlying the perception of dissonance at the level of the sensory organ are generalized to all pitch intervals at later, more centrally located, neural stages. Support for this view comes from the study of a patient, IR, presenting a selective loss of dissonance perception after bilateral damage to the superior temporal gyri (Peretz *et al.*, 2001) and from another study using intracranial recording that showed specific activity in human and macaque primary auditory cortex in response to dissonance (Fishman *et al.*, 2001). Thus, the auditory cortex appears to be involved in the perceptual analysis of dissonance.

Dissonance also appears to recruit paralimbic regions. Using positron emission tomography, Blood and her collaborators (1999) observed activity within paralimbic and cortical brain regions in response to dissonance. Increases of activity in the right parahippocampal gyrus (PHG) and decreases of activity in the orbitofrontal and in the subcallosal cingulate areas were observed for dissonant music as compared to consonant music. Using functional magnetic resonance imaging, Koelsch *et al.* (2006) recently found not only increased activation in the PHG, but also in the amygdala, the hippocampus and the temporal poles. In order to clarify the differential roles played by these regions in the emotional evaluation of dissonance, we sought to assess dissonance perception in a group of epileptic patients with varying degrees of resection in these same brain regions.

In summary, current evidence suggests that dissonance may recruit paralimbic structures and auditory cortices. The paralimbic regions seem to be associated with the emotional evaluation of dissonance (Blood *et al.*, 1999; Koelsch *et al.*, 2006), while the auditory cortex seems to be more involved in its perceptual analysis (Blood *et al.*, 1999; Peretz *et al.*, 2001). Accordingly, lesions up to the auditory cortex will result in a deficit in dissonance perception and consequently, will prevent its emotional processing as seen in the case study of IR (Peretz *et al.*, 2001). Conversely, lesions in paralimbic regions will result in indifference to dissonance despite its intact perception. Testing epileptic patients with lesions limited to the paralimbic regions should allow us to test this account.

To this aim, we examined the emotional evaluation of dissonant music by groups of epileptic patients with anteromedial temporal lobe excision including the whole amygdala, and variable amounts of parahippocampal, perirhinal, entorhinal and hippocampal tissue. Here, we focus primarily on the PHG, because of the two prior neuroimaging studies linking this structure to the processing of dissonant music (Blood *et al.*, 1999; Koelsch *et al.*, 2006). We tested two groups of epileptic subjects: those with lesions in whom MRI volumetric measurements showed a significant removal of the parahippocampal cortex (PHC-resected) and those with lesions that tended to spare the PHC (PHC-preserved). In order to assess the specific impact of amygdala damage on the emotional evaluation of dissonant music, we also tested subject SM, who has bilateral and selective damage to the amygdala (with complete sparing of PHC; Adolphs and Tranel, 2000). For all of these patients, the damage spares the auditory cortex. Participants were presented with the same material and task used with IR, the patient with damage to the auditory cortex but spared limbic system (Peretz *et al.*, 2001). The patients were requested to rate the degree of pleasantness of consonant and dissonant versions of the same happy or sad musical excerpts. On half of the trials, a pitch-shift of one semitone was applied to the leading voice of the musical excerpts so as to create dissonance, following the procedure used with infants (Trainor and Heinmiller, 1998). If emotional evaluation of dissonance recruits the PHG (Blood *et al.*, 1999), then only those patients with a medial temporal lobe resection encompassing the PHC would be impaired. Alternatively, if the amygdala is a critical neural structure (e.g. Koelsch *et al.*, 2006), then both SM and the patients with medial temporal resection would be impaired in this task, and show little sensitivity to the presence of dissonance in their pleasantness judgements.

In order to assess whether the expected deficit in pleasantness judgements was specific to dissonance, participants were also required to perform happy–sad judgements on the same musical excerpts. We expected SM (Gosselin *et al.*, 2006) and the epileptic patients (Gosselin *et al.*, 2005) to perform normally on these happy–sad judgements. This task also allows us to examine the influences of dissonance on happy–sad judgements (Peretz *et al.*, 2001). In order to assess the integrity of perceptual processes, a pitch shift detection task was also administered.

Material and method

Participants

Seventeen patients with left or right unilateral anteromedial temporal lobe resection for the relief of medically intractable epilepsy participated in this study. These patients were operated at La Salpêtrière Hospital (Paris). All had a medial temporal

lobe resection, including the whole amygdala as well as various amounts of the parahippocampal, entorhinal, perirhinal cortices and the hippocampus. The excision also included the temporal pole in all of our patients, except for two patients (*see* Table 1). However, the removal never encroached into the superior temporal gyrus. High-resolution MRI volumetric measurements of medial temporal lobe structures were carried out using a protocol initially proposed by Hasboun *et al.* (1996) and by Insausti *et al.* (1998). The patients underwent imaging with a 1.5-T MR scanner using a standard head coil and tilted coronal 3D magnetization-prepared rapid acquisition gradient-echo sequence with the following parameters: 14.3/6.3/1 (TR/TE/excitation). This resulted in 124 contiguous T1-weighted partitions with a 1.5 mm section thickness oriented perpendicular to the long axis of hippocampus. These MRI volumetric measurements led to the identification of 10 patients with a significant resection of the PHC; that is, with a remaining volume being 2 SD below the mean of the 16 normal controls (*see* Table 1); the other 7 patients had no significant resection of this region. The PHC corresponds to the posterior portion of the PHG; the anterior portion of the PHG is divided into the entorhinal and perirhinal cortex. The extent of removal was calculated following the segmentation guidelines developed by Pruessner *et al.* (2002) and extended by Noulhiane *et al.* (2006) to the volumetric study of patients with medial temporal lobe resection from the MRI. Table 1 summarizes the remaining volumes of the parahippocampal, perirhinal and entorhinal cortex, and the hippocampus of each patient. The remaining volumes did not differ between the two groups (all $P > 0.05$), except for the PHC ($P < 0.005$, by Mann–Whitney tests). An illustration of a representative excision is displayed in Fig. 1.

In the majority of cases, the cause of seizures was hippocampal sclerosis dating from birth or early life. Patients with EEG

Table 1 Remaining volumes of the resected side for parahippocampal, perirhinal and entorhinal cortex and hippocampus for each patient with significant PHC-resected and with a relative PHC-preserved

Participants	Side	Parahippocampal (cm^3)	Perirhinal (cm^3)	Entorhinal (cm^3)	Hippocampus (cm^3)
PHC-resected					
PHC01	L	1.57	0	0	0.30
PHC02	L	1.74	0.31	0.33	0.10
PHC03	L	1.20	0.17	0.01	0.20
PHC04	L	1.35	0	0	0.10
PHC05	L	1.57	0.52	0.22	0.20
PHC06	L	1.57	0.28	0.00	0.30
PHC07	R	1.56	0.61	0.19	0.40
PHC08	R	1.68	0.22	0.16	0.11
PHC09	R	1.74	0.21	0	0
PHC10	R	0.59	0	0	0
	Mean	1.46	0.23	0.09	0.17
PHC-preserved					
PHC11	L	2.11	0.73	0.53	0.60
PHC12	L	2.17	0.65	0.34	0.20
PHC13	R	1.83	0.07	0	0
PHC14*	R	1.99	1.34	0.19	0.30
PHC15	R	1.93	0.05	0	0.60
PHC16	R	2.23	0.50	0.21	0.10
PHC17*	R	1.76	3.08	1.94	3.65
	Mean	2	0.92	0.46	0.78
Normal controls		Mean (SD)			
	L	2.45 (0.27)			
	R	2.49 (0.37)			

Mean volumes (and SD) of the left and right PHC in normal controls are also provided. L = left; R = right.
*Two patients for which the temporal pole was not completely resected.

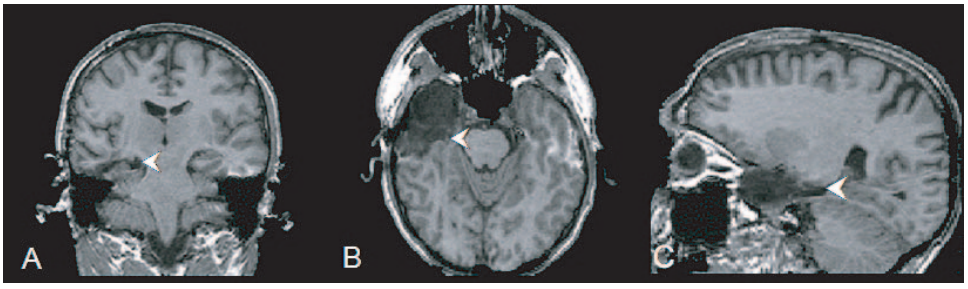

Fig. 1 The T1 MRI of a representative anteromedian temporal lobe resection of a patient with a significant left excision of the PHC is displayed in three planes: coronal (**A**), axial (**B**) and sagittal (**C**). The arrows point to the resected PHC.

Table 2 Mean (and SD) of age, education and IQ for PHC-resected and PHC-preserved patients, SM and normal controls

	PHC-resected	PHC-preserved	SM	Normal controls
Sex				
Male	6	4		9
Female	4	3	1	10
Age (years)	42.6 (9)	37.3 (8)	38	39.7 (8)
Education (years)	12 (2)	15 (2)	11/High school	13 (3)
IQ	95 (10)	105 (12)	86	—

abnormality, evidence of fast-growing tumours, or diffuse cerebral damage were excluded from the study. Similarly, subjects with atypical speech representation (as determined via intracarotid sodium amytal testing; Wada and Rasmussen, 1960) and full-scale intelligence quotient (IQ, Wechsler Adult Intelligence Scale Revised) score <75 were excluded. Patients were tested between 5 months and 8.3 years post-operatively and they were all seizure free at the time of testing. All were non-musicians; their age, education and IQ are presented in Table 2. The demographic variables did not differ between the two patient groups (all $P > 0.05$, by two-tailed t tests) except for education ($P < 0.05$). Patients with PHC resection were slightly less educated. Hence, a possible impact of education on test scores was statistically assessed, but it was found to be negligible.

SM also participated in the present study. She has complete bilateral damage to the amygdala and has been extensively studied by Adolphs and collaborators over the past decade (*see* Adolphs and Tranel, 2000, for a detailed account of her neuroanatomical and neuropsychological profile). SM's damage encompasses all nuclei within the amygdala as well as anterior portions of entorhinal cortex, yet sparing all other subcortical and cortical structures. As a result, SM has essentially normal basic perception, memory and language, as long as it does not involve emotional material. SM is a typical non-musician who occasionally listens to music. As shown in a prior study (Gosselin *et al.*, 2006), SM is normal at distinguishing the happy from the sad consonant versions of the musical stimuli used here.

The normal control group (NC) included 19 non-musicians with no neurological or psychiatric history and selected to match SM and the epileptic patients as closely as possible in term of age, sex and education (*see* Table 2). All participants gave written informed consent before testing, in accordance with the Declaration of Helsinki.

Emotional test

Twenty-four excerpts were taken from the set used in previous studies (Peretz *et al.*, 1998, 2001). All were instrumental in that they were not originally sung with lyrics; they were drawn from the corpus of Western classical music. These excerpts were selected so that half evoked a sense of happiness and the other half a sense of sadness. Happy selections were written in major mode (e.g. 'Brindisi' from Verdi's *Traviata*) and were played at a fast tempo (the quarter note value varies from 80 to 255, conventionally written by M.M. for metronome marking); sad selections were written in minor mode (e.g. Albinoni's Adagio) and were played at a slow tempo (between 20 and 100 M.M.). These excerpts lasted on average 15 s (range: 6–32 s) and corresponded to the consonant versions. The dissonant versions were created by shifting the pitch of all tones of the leading voice by one semitone either upward or downward (*see* Fig. 2 for an example).

In sum, the experiment was composed of 24 consonant excerpts repeated two times and 48 dissonant versions (i.e. 24 upward and 24 downward). One example of a consonant version with its two altered versions (i.e. upward and downward) can be heard at www.brams.umontreal.ca/peretz. Four sets, each including 48 stimuli, were constructed with these excerpts. In each set, half the excerpts were consonant and half were dissonant, with an equal number of sad and happy stimuli in each version. In each set, stimuli were presented in a pseudo-random order.

All stimuli were transcribed for piano and computer-generated on a microcomputer running a MIDI sequencing program (Sequencer Plus Gold) in a piano timbre. The MIDI files were digitally recorded onto compact disks and delivered to the participants in free field at a loudness level that was comfortable for them.

Each participant was tested individually in two sessions, each lasting ~1 h, following an ABBA design. In each session, they were required to perform two different tasks, a happy–sad judgement task (A), and a pleasant–unpleasant judgement task (B). For each task requirement (A and B), subjects were presented with one of the four sets, hence with 48 musical selections to evaluate. All participants were tested in the AB followed by the BA order. They were required to evaluate the emotional tone that they felt corresponded to the presented selection and to respond on a 10-point scale. For the happy–sad judgement task (A), 1 meant 'triste'/sad and 10 meant 'gai'/happy. For the pleasant–unpleasant judgement task (B), 1 meant 'désagréable'/unpleasant and 10 meant 'agréable'/pleasant. No further information or feedback was given to the participants.

Perceptual test

Eighteen excerpts were selected from the stimuli used in the emotional test so as to allow deviation of a single measure (*see* Peretz *et al.*, 1998, for a similar use of the stimuli). The changes affected the pitch of all tones of the leading voice comprised in a single measure, by either shifting the pitch of each note one semitone higher or lower. Thus, there were two modified measures for each intact excerpt: one measure with an upward pitch-shift and one with a downward shift. These 36 modified excerpts were randomly mixed with 36 intact versions (corresponding to the 18 intact excerpts repeated two times). To provide as much context as possible, the deviation never occurred on the initial and last measure of the excerpt.

The participants were requested to detect whether or not the pianist lost track of what he was playing at some point in the piece. There were two examples before the experimental ones. Subjects were not informed of the nature of the changes and no feedback was provided, except for the two examples. The session lasted ~45 min and was presented after the emotional test.

Results and comments

Perceptual test

The percentages of correct responses ('yes' responses to the presence of an error and 'no' responses to an intact stimulus) were computed for each patient and normal

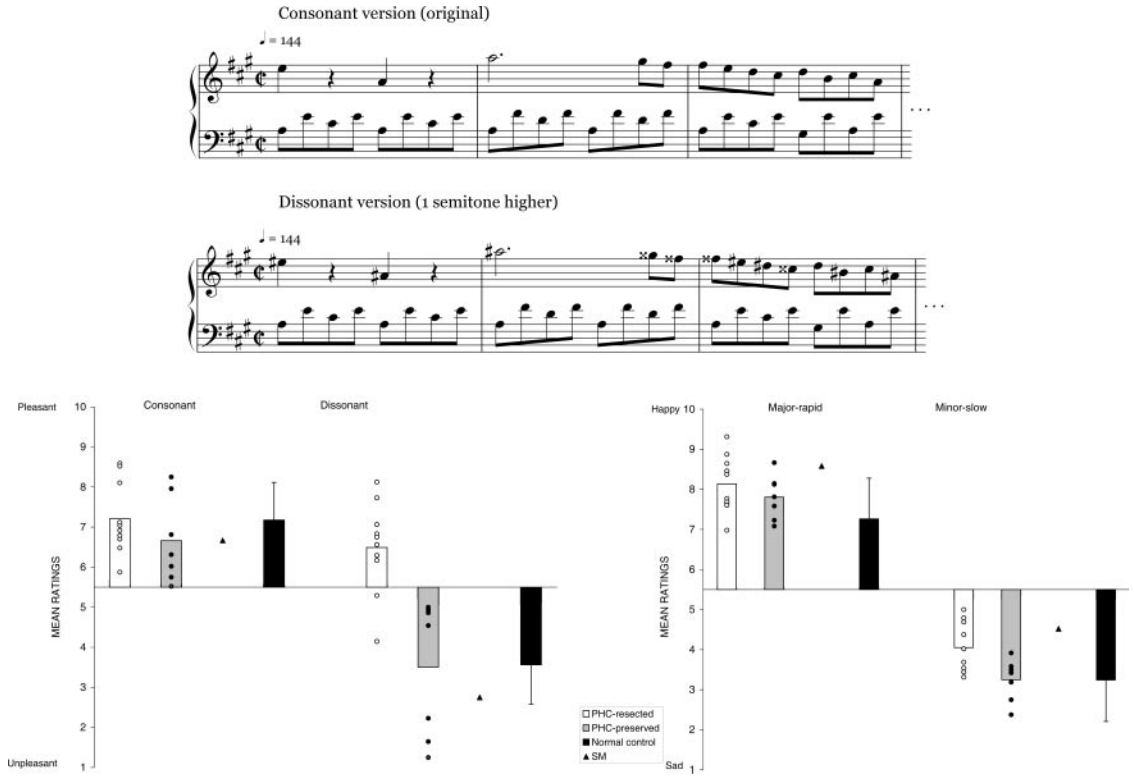

Fig. 2 In the top, an example of the musical notation for the beginning of consonant and dissonant versions of an excerpt is represented. In the bottom, the ratings obtained in the pleasant–unpleasant task (*left panel*) and the happy–sad task (*right panel*) are presented for each patient from the PHC-resected (white bar and circles), the PHC-preserved (grey bar and black circles), for subject SM (black triangle), and normal controls (black bars). SEM is shown for the NC group.

control in the error detection task. Percentage of correct responses was 77% (SD = 9) for the normal controls, 72% (SD = 10) for the PHC-resected patients, 80% (SD = 12) for the PHC-preserved patients and 82% for SM. All participants performed well above chance (50%). The PHC groups did not differ significantly from the controls [$F(2,33) = 1.49$, $P > 0.05$, and $\chi^2 = 3.55$, d.f. = 2, n.s., by Kruskal–Wallis test]. Similarly, SM performed within 2 SD of the mean obtained by the normal control and patient groups.

Emotional test

As can be seen in Fig. 2, PHC-preserved patients and subject SM judged the consonant excerpts as pleasant and the dissonant versions as unpleasant, as did the controls. However, the PHC-resected patients judged the dissonant stimuli to be significantly more pleasant than did either the normal controls ($z = -4.06$, $P < 0.001$, Mann–Whitney test) or the PHC-preserved group ($z = -3.03$, $P < 0.005$). In contrast, they did not differ significantly from controls ($z = -0.14$, n.s.) and the PHC-preserved groups ($z = -1.37$, n.s.) in judging the consonant music. We followed up the pairwise contrasts using resampling, which confirmed that the only statistically significant differences were between the PHC-resected group and the PHC-preserved group [95% confidence interval (CI) = −4.42, −1.73] or the controls (95% CI = −3.69, −2.07) when rating the pleasantness of dissonant music. The side of resection did not influence the outcome; the PHC-resected patients with a left ($n = 6$) and a right temporal resection ($n = 4$) did not differ from each other (all comparisons being n.s., by Mann–Whitney tests). As can be noted in Fig. 2, one PHC-resected patient (PHC05, *see* Table 1) judged the dissonant stimuli as unpleasant, as did the other participants. The reason for this sparing is unclear. Size of the remaining PHC, age, education and IQ cannot account for the sparing. Finally, SM performed within 2 SD of the mean ratings given by both normal control and PHC-preserved groups.

The contribution of the PHC to the appraisal of unpleasant music is further supported by a significant correlation between the remaining volume measured from the magnetic resonance imaging scans and the individual ratings. As can be seen in Fig. 3, the larger the removal (the less remaining tissue) in the PHC, the more impaired was the pleasantness rating (Spearman correlation $r = -0.72$, d.f. = 15, $P < 0.005$). The correlation was not significant for the pleasant (consonant) music ($r = -0.36$, n.s.). Since the sample sizes were small, we also calculated an exact statistic using re-sampling. This yielded for the dissonant stimuli a Pearson $r = -0.58$, $P < 0.02$. No other correlations were significant (we tested all possible correlations between neuroanatomical volumes and scores on consonant or

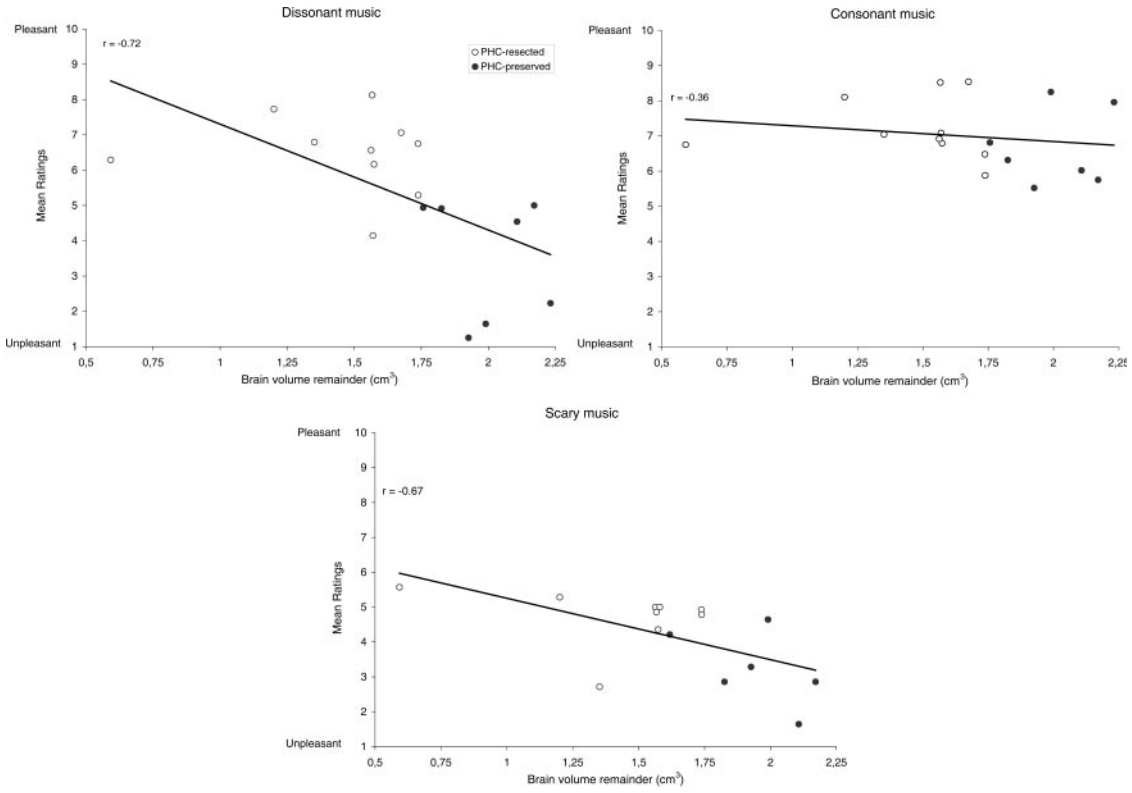

Fig. 3 The correlation between individual ratings on the pleasant–unpleasant scale and remaining neural tissue in the PHC is plotted for the dissonant (*left panel*), the consonant music (*right panel*) and scary music (lower panel). Open circles represent PHC-resected patients and black circles, PHC-preserved patients.

dissonant music), and neither was the correlation with the total resected volume. As a further test of the specificity of the PHC role in the judgement of dissonant music, we calculated the partial correlations between the PHC volume and the ratings, which partials out the effect of entorhinal, perirhinal or hippocampal volumes. The correlation remained significant using two-tailed testing ($r = -0.54$, d.f. = 12; $P < 0.05$, *see* Table 3). These results confirm the neuroanatomical specificity of the relation between the PHC volume and the unpleasant responses to dissonant music.

The role of the PHC also appears to be specific in terms of emotion processing, since damage did not interfere with appreciation of pleasant (consonant) music and was not associated with a loss of all emotional judgements (as for the happy and sad judgements; cf. Fig. 2). However, the PHC-resected group seems to judge the major-rapid music to be happier than normal controls ($z = -2.32$, $P < 0.05$, by Mann–Whitney test) and the minor-slow music to be less sad than did normal controls and PHC-preserved patients ($z = -2.07$ and $z = -2.30$, respectively, both $P < 0.05$). These differences in emotional evaluation can be related to the lack of sensitivity to dissonance exhibited by the PHC-resected group. As can be seen in Fig. 4, the difference in happy–sad judgements between the PHC-resected patients and the other participants essentially emerge for the dissonant stimuli. The PHC-resected patients did not differ from other groups ($z = -0.80$ and $z = 0.35$, for normal controls and PHC-preserved, respectively, both $P > 0.05$, by Mann–Whitney tests) in judging the major-rapid music when it was consonant but they judged it happier when the music was dissonant ($z = -2.89$, $P < 0.01$, compared with normal controls). Similarly, their judgement of sadness did not differ from controls and PHC-preserved patients when the minor-slow music was consonant ($z = -1.56$ and $z = -1.86$, respectively, both $p > 0.05$) but differed when it was dissonant ($z = -2.55$ and $z = -2.54$, respectively, both $P < 0.05$).

Finally, subject SM, who has selective damage to the amygdala, judged the dissonant music as unpleasant as normals did (*see* Fig. 2). This finding is in line with a prior neuroimaging study that observed activity in the PHG, and

Table 3 Partial correlations (two-tailed tests) between the pleasant–unpleasant ratings given by the 17 patients on the dissonant stimuli as a function of the remaining volumes of the medial temporal structures

Correlated structure	Controlled variables	Partial correlations (d.f. = 12)
PHC	Entorhinal+perirhinal+hippocampus	$r = -0.54$, $P < 0.05$
Entorhinal	PHC+perirhinal+hippocampus	$r = 0.32$, n.s.
Perirhinal	PHC+entorhinal+hippocampus	$r = -0.35$, n.s.
Hippocampus	PHC+entorhinal+perirhinal	$r = -0.09$, n.s.

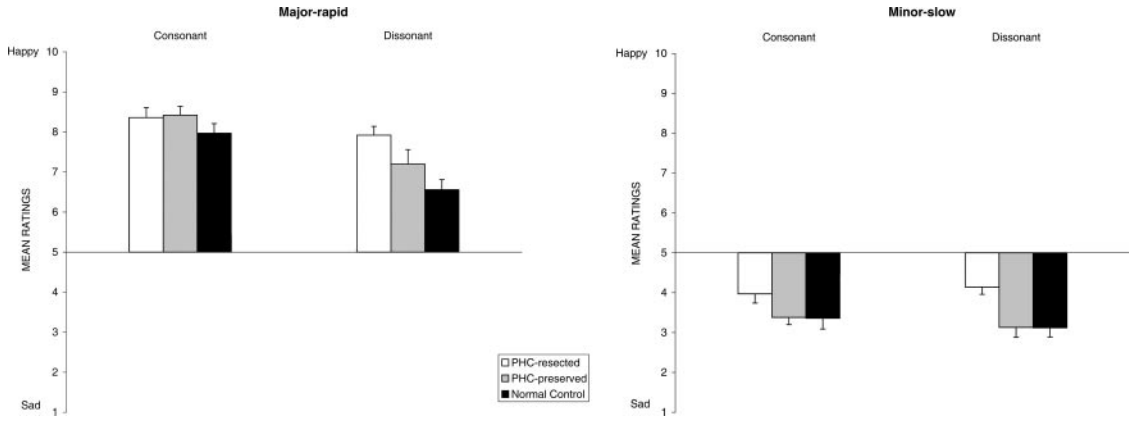

Fig. 4 The ratings obtained in the happy–sad task are presented as a function of structure of the music (major-rapid and minor-slow) and the version presented (consonant and dissonant) for PHC-resected (white bars), PHC-preserved (grey bars), and normal controls groups (black bars). SEM is also shown for each group.

not in the amygdala, in response to dissonant music (Blood *et al.*, 1999). Furthermore, while SM has difficulty judging that music is scary, she nonetheless correctly rated it as unpleasant (Gosselin *et al.*, 2006). This spared valence judgement for scary music might be related to her intact PHC. If so, then damage to the PHC should diminish the unpleasant experience elicited by scary music. To test this final prediction, we re-analysed the data from our prior study (Gosselin *et al.*, 2005). Sixteen control subjects, nine of the PHC-resected patients, six of the PHC-preserved patients as well as SM had participated in this prior study (Gosselin *et al.*, 2005, 2006) in which the ability to recognize scary music was studied. Their scores on pleasant–unpleasant task for scary music are presented in Fig. 3. As can be seen, the volume of the PHC correlates with the individual ratings of pleasantness obtained with the scary music (Spearman $r = -0.67$, d.f. = 13, $P < 0.01$). This retrospective analysis of our prior data confirms the critical role of the PHC in the appraisal of unpleasantness in music, by extending its contribution to judging the unpleasantness of scary music.

Discussion and conclusion

The present study shows that an anteromedial temporal lobe resection, including a significant removal of the PHC, results in a diminished sensitivity to unpleasant (dissonant) music. The larger the removals of the PHC, the more indifferent to dissonance were the patients. This indifference to dissonance also modulated the happy–sad responses, so that happy dissonant music remained as happy as consonant music and vice versa for the sad music. This indifference to dissonance is atypical. As mentioned earlier, ordinary listeners judge the dissonance introduced in highly conventional music as done here, rather aversive (Plomp and Levelt, 1965; Wedin, 1972; Zentner and Kagan, 1996; 1998; Trainor and Heinmiller, 1998; Blood *et al.*, 1999; Costa *et al.*, 2000; Peretz *et al.*, 2001; Trainor *et al.*, 2002; Koelsch *et al.*, 2006). Such a negative response to dissonance was replicated here in all participants but the group with significant removal of the PHC, who judged the dissonant stimuli as moderately pleasant. Thus, the PHC appears as a critical brain area involved in judging unpleasant music, in line with prior neuroimaging results (Blood *et al.*, 1999; Koelsch *et al.*, 2006). The novelty of the present findings is that these point to the PHC as an essential structure among all the identified brain areas (the amygdala, temporal pole and hippocampus).

The contribution of the PHC appears specific to the emotional interpretation of dissonance because its removal does not affect perception of dissonance *per se* nor does it affect all emotional evaluation of music. The PHC-resected patients detected the pitch-shift changes that are responsible for the dissonance studied here. Moreover, the emotional evaluation of happy and sad consonant music was spared after the PHC resection.

In contrast, the amygdala, temporal pole and hippocampus did not contribute to the judgements of unpleasantness. In particular, there was no evidence that the volume of the hippocampus contributed to the unpleasantness ratings beyond the contribution of the PHC, in line with the PET study of Blood *et al.* (1999). Nevertheless, the fMRI study of Koelsch *et al.* (2006) reported activation in the hippocampus; hence, its possible implication in normal processing of emotions cannot be ruled out on the basis of the present data. What the present data do suggest is that the hippocampus is not essential for the appraisal of unpleasant music.

Similarly, the amygdala was not critical for valence appraisal, and appears to be more involved in the recognition of scary music (Gosselin *et al.*, 2005, 2006) and of other fear-related stimuli (Adolphs *et al.*, 1994; Calder *et al.*, 1996; Scott *et al.*, 1997; LaBar *et al.*, 1998; LeDoux, 2000). These results support a functional segregation between the PHC

and the amygdala in evaluating aversive stimuli. The emotional saliency associated with unpleasant experiences might depend on the amygdala (Anderson *et al.*, 2001) while their avoidance may instead rely on the PHG. Because the PHG and the amygdala have strong reciprocal connections (Stefanacci *et al.*, 1996), these two brain structures may function as two components of a neural system that helps the organism to cautiously explore and protect itself from potentially harmful experiences (McNaughton and Corr, 2004). Analyses of dynamic functional connectivity between these two regions should provide a deeper understanding of how the brain responds to aversive signals. Future examination of the functions of the connections between the PHG, the amygdala and the other neural structures (e.g. the hippocampus) should shed light on emotional processing and its well-known association to memory. Music may again be instrumental in this endeavour because of its rich and temporal nature that enables on-line monitoring of connectivity between distinct brain structures.

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