CORTEX 130 (2020) 78–93

Available online at www.sciencedirect.com

ScienceDirect

Journal homepage: www.elsevier.com/locate/cortex

Special Issue "Brain and cognitive asymmetry in clinical disorders": Research Report

Recognition of musical emotions and their perceived intensity after unilateral brain damage

Agathe Pralus [a,b,1,*], Amy Belfi [d,1], Catherine Hirel [a,b,e,1], Yohana Lévêque [a,b], Lesly Fornoni [a,b], Emmanuel Bigand [f], Julien Jung [a,b,e], Daniel Tranel [c], Norbert Nighoghossian [b,e,g], Barbara Tillmann [a,b,1] and Anne Caclin [a,b,1]

[a] Lyon Neuroscience Research Center; CNRS, UMR5292; INSERM, U1028; Lyon, France
[b] University Lyon 1, Lyon, France
[c] Department of Neurology, University of Iowa, Iowa City, IA, USA
[d] Department of Psychological Science, Missouri University of Science and Technology, Rolla, MO, USA
[e] Hôpital Neurologique Pierre Wertheimer, Hospices Civils de Lyon, Bron, France
[f] LEAD, CNRS, UMR 5022, University of Bourgogne, Dijon, France
[g] CREATIS, CNRS, UMR5220, INSERM, U1044, University Lyon 1, France

ARTICLE INFO

Article history:
Received 30 December 2019
Reviewed 21 April 2020
Revised 27 May 2020
Accepted 29 May 2020
Published online 12 June 2020

Keywords:
Brain lesion
Emotion perception
Music
Right hemisphere hypothesis
Valence hypothesis

ABSTRACT

For the hemispheric laterality of emotion processing in the brain, two competing hypotheses are currently still debated. The first hypothesis suggests a greater involvement of the right hemisphere in emotion perception whereas the second hypothesis suggests different involvements of each hemisphere as a function of the valence of the emotion. These hypotheses are based on findings for facial and prosodic emotion perception. Investigating emotion perception for other stimuli, such as music, should provide further insight and potentially help to disentangle between these two hypotheses. The present study investigated musical emotion perception in patients with unilateral right brain damage (RBD, n = 16) or left brain damage (LBD, n = 16), as well as in matched healthy comparison participants (n = 28). The experimental task required explicit recognition of musical emotions as well as ratings on the perceived intensity of the emotion. Compared to matched comparison participants, musical emotion recognition was impaired only in LBD participants, suggesting a potential specificity of the left hemisphere for explicit emotion recognition in musical material. In contrast, intensity ratings of musical emotions revealed that RBD patients underestimated the intensity of negative emotions compared to positive emotions, while LBD patients and comparisons did not show this pattern. To control for a potential generalized emotion deficit for other types of stimuli, we also tested facial

Abbreviations: RBD, Right-brain damage; LBD, Left-brain damage; MBEA, Montreal Battery of Evaluation of Amusia; PDT, Pitch Discrimination Threshold; MMSE, Mini Mental State Examination; WAIS-IV, Wechsler Adult Intelligence Scale; WCST, Wisconsin Card Sorting Test; MEC, Montreal Evaluation of Communication; AVLT, Auditory-Verbal Learning Test; BNT, Boston Naming Test; COWA, Controlled Oral Word Association.

* *Corresponding author*. CRNL, 95 Bd Pinel, 69675, Bron Cedex, France.
E-mail address: agathe.pralus@inserm.fr (A. Pralus).

[1] Equally contributing authors.

https://doi.org/10.1016/j.cortex.2020.05.015

emotion recognition in the same patients and their matched healthy comparisons. This revealed that emotion recognition after brain damage might depend on the stimulus category or modality used. These results are in line with the hypothesis of a deficit of emotion perception depending on lesion laterality and valence in brain-damaged participants. The present findings provide critical information to disentangle the currently debated competing hypotheses and thus allow for a better characterization of the involvement of each hemisphere for explicit emotion recognition and their perceived intensity.

1. Introduction

Studying perception in brain-damaged patients has contributed to a better understanding of various brain functions, including emotion perception. Seminal studies have investigated brain-damaged patients' emotion processing in faces and voices, aiming for a better understanding of patients' communication with their social environment (Borod, 1992; Peretz, 1990; Peretz, Gagnon, & Bouchard, 1998; Sackeim et al., 1982). For facial emotion recognition, results consistently describe increased difficulties for brain-damaged patients to recognize facial emotions in comparison with controls (Borod, Bloom, Brickman, Nakhutina, & Curko, 2002; Charbonneau, Scherzer, Aspirot, & Cohen, 2003; Cheung, Lee, Yip, King, & Li, 2006; Harciarek, Heilman, & Jodzio, 2006). However, the degree of impairment seems to depend on lesion location (Yuvaraj, Murugappan, Norlinah, Sundaraj, & Khairiyah, 2013). For example, lesions in subcortical structures, such as thalamus and basal ganglia, have been associated only with a small decrease in facial emotion recognition compared to controls (Cheung et al., 2006). When the lesion involves cortical regions, the degree of impairment for facial emotion recognition varies according to the damaged area, with more impairment for anterior brain lesions than posterior lesions, in particular for negative valence emotions (Harciarek & Heilman, 2009).

Numerous studies have investigated the effect of lesion laterality on (facial and prosody) emotion recognition, with findings resulting in two contrasting hypotheses. The *Right Hemisphere Hypothesis* suggests that the right hemisphere is dominant for emotion processing independently of the type of emotion, while the *Valence Hypothesis* suggests that positive emotions are preferentially processed in the left hemisphere whereas negative emotions are preferentially processed in the right hemisphere (Abbott, Cumming, Fidler, & Lindell, 2013; Adolphs, Jansari, et al., 2001). In support of the Right Hemisphere Hypothesis, numerous studies have reported stronger emotion recognition impairments in right brain-damaged (RBD) patients compared to left brain-damaged (LBD) patients and to controls (Adolphs, Tranel, & Damasio, 2001; Borod, Bloom, Brickman, Nakhutina, & Curko, 2002; Charbonneau et al., 2003; Harciarek et al., 2006; Kucharska-Pietura, Phillips, Gernand, & David, 2003a; Tippett et al., 2018), without potential interaction with the valence of the emotions. Notably, a meta-analysis on facial emotion recognition in brain-damaged patients suggests more involvement of the right hemisphere for emotion perception as RBD patients were more impaired than were LBD patients. However, it also suggests a right lateralization specific for negative valence emotion perception, but no lateralization for positive valence emotion perception (Abbott et al., 2013). In support of the Valence hypothesis, recent studies reported a specific deficit of RBD patients for negative emotions (Braun, Traue, Frisch, Deighton, & Kessler, 2005; Nijboer & Jellema, 2012). This finding is in line with the observation that right-hemisphere lesions were associated to pathological laughing and euphoric mood change, while left-hemisphere lesions were associated to pathological crying (Sackeim et al., 1982). Yet other studies also reported impaired emotion perception for both RBD and LBD patients without lateralization of the deficit and no clear link with the valence of the emotion (Abbott, Wijeratne, Hughes, Perre, & Lindell, 2014; Braun, Traue, Frisch, Deighton, & Kessler, 2005; Cheung et al., 2006). Overall, the results regarding brain lateralization and emotion perception are still unclear, with no clear-cut evidence for one specific hypothesis, at least when emotion processing was studied with face stimuli (Abbott et al., 2013).

As emotions can be communicated not only via visual cues, but also auditory cues, some studies have investigated vocal emotion perception, such as emotional prosody, in brain-damaged patients (see Yuvaraj et al., 2013 for a review). Most studies using language and vocalization materials were in support of the Right Hemisphere Hypothesis, reporting greater impairment of RBD patients for emotional prosody recognition than LBD patients and controls (Borod et al., 2002; Charbonneau et al., 2003; Harciarek et al., 2006; Kucharska-Pietura, Phillips, Gernand, & David, 2003). Another study confirmed the deficit for RBD patients, which was larger than for LBD patients, but for this one study, the LBD patients also had a mild impairment for emotional prosody compared to controls (Kucharska-Pietura et al., 2003).

Overall, numerous studies investigating emotion perception in brain-damaged patients with facial and prosody materials have revealed complex patterns of impairments depending both on lesion lateralization and lesion localization. Only few studies have investigated musical emotions in brain-damaged patients, even though emotions are an important motivation for music listening (Egermann, Fernando, Chuen, & McAdams, 2014). In the musical domain, it has been shown that emotion recognition can be

preserved in patients even when their musical structure perception is impaired (Peretz et al., 1998). Several case reports have revealed that brain damage can result in musical anhedonia, a specific loss of experience of pleasure for music whereas emotion recognition is intact (Belfi, Evans, Heskje, Bruss, & Tranel, 2017; Griffiths, Warren, Dean, & Howard, 2004; Satoh, Nakase, Nagata, & Tomimoto, 2011, 2016). For instance, a patient with a right inferior parietal lobe infarct did not perceive any emotion when listening to music, but its music perception and emotion recognition were preserved (Satoh et al., 2011). Case reports (Gosselin, Peretz, Johnsen, & Adolphs, 2007; Griffiths et al., 2004; Satoh et al., 2016) and group studies (Gosselin, Peretz, Hasboun, Baulac, & Samson, 2011; Jafari, Esmaili, Delbari, Mehrpour, & Mohajerani, 2017; Khalfa et al., 2007, 2008) have also reported deficits of music emotion recognition in brain-damaged patients. For instance, patients with unilateral medial temporal lesions showed more difficulties to recognize musical emotions, especially for fearful stimuli (Gosselin et al., 2011), with no clear association to one side of the lesion. Regarding the potentially differentiated roles of the two hemispheres for musical emotion recognition, it has been observed that patients with right temporal lobe lesions have more difficulties in recognizing emotions in music than patients with left temporal lobe lesions (Jafari et al., 2017). More precisely, these RBD patients had greater difficulties in recognizing negative emotions such as sadness compared to LBD patients (Jafari et al., 2017; Khalfa et al., 2007), whereas LBD patients had greater difficulties in recognizing positive emotions such as happiness (Khalfa et al., 2007), in keeping with the predictions of the Valence Hypothesis. These results were consistent with the studies of musical emotion perception in healthy participants that demonstrate a lateralization of this perception according to the valence of the emotion (Altenmüller, Schürmann, Lim, & Parlitz 2002; Tsang, Trainor, Santesso, Tasker, & Schmidt, 2001). In another study, RBD patients overestimated the arousal for happiness in music, compared to LBD patients (Khalfa et al., 2008). However, when asked to judge emotional dissimilarities in musical excerpts in terms of arousal and valence instead of emotion recognition, patients with left or right unilateral medial temporal lesions did not show any deficit (Dellacherie, Bigand, Molin, Baulac, & Samson, 2011). This was consistent with results reported for healthy participants that showed no clear pattern regarding brain lateralization of valence for musical perception (Khalfa, Schon, Anton, & Liégeois-Chauvel, 2005).

Variability in the results regarding musical emotions processing of previous studies might be related to the diversity of experimental paradigms. Some studies used musical emotion categorization tasks (Gosselin et al., 2011; Jafari et al., 2017; Peretz et al., 1998) and others required ratings of the emotions' intensity (Gosselin et al., 2007; Griffiths et al., 2004) or ratings of valence and arousal (Dellacherie et al., 2011; Gosselin et al., 2007; Khalfa et al., 2008; Satoh et al., 2011). As previously suggested in studies with facial and prosodic material in healthy participants and unilateral brain-damaged patients (Abbott et al., 2013; Borod et al., 2002; Demaree, Everhart, Youngstrom, & Harrison, 2005), these task effects could reflect the distinction between the recognition and the actual experience of emotions. Indeed, some studies have suggested that the right hemisphere hypothesis would be more strongly associated with emotion recognition, i.e., with a cognitive or intentional process, whereas the valence hypothesis would be more strongly associated with automatic processing of the emotion and thus being closer to the emotional experience of participants (Abbott et al., 2013; Borod et al., 2002; Demaree et al., 2005). These two modes of emotional processing would rely on different anatomical substrates, with emotion recognition associated with hemispheric asymmetries in posterior and temporal regions, whereas emotion experience would be associated with hemispheric asymmetries in more frontal regions (Abbott et al., 2013; Borod, 1992). To further contribute to the distinction between these two processes in association with the two hypotheses of emotion processing in music, tn the present study, a two-task paradigm was used to assess both musical emotion categorization and intensity ratings of these emotions in unilateral brain-damaged patients and matched healthy comparison participants. In this paradigm, participants were required to choose the recognized emotion among four possibilities (Joy, Fear/Anger, Sadness, or Neutrality/Serenity) in musical, and then to rate the intensity of this emotion on a five-point scale. The intensity of emotions can be done without verbal or categorical representation of the emotion as a global appreciation of the stimulus or a fuzzy representation of emotion suffices (Lévêque et al., 2018). Intensity ratings of emotions reflect a more implicit perception of the emotion and could be closely related to the actual feeling of this emotion (Hirel et al., 2014). In previous studies, this paradigm has allowed us to show that emotion recognition, but not intensity ratings of these emotions, is disrupted in congenital amusia, both for musical material (Lévêque et al., 2018) and emotional prosody material (Pralus et al., 2019). This paradigm also allowed for the identification of emotion recognition deficits without intensity ratings deficits in single cases of brain-damaged patients: in one patient with musical material (Hirel et al., 2014) and in another patient with emotional prosody material (Bourgeois–Vionnet, Moulin, Hermier, Pralus, & Nighoghossian, 2020). Furthermore, participants were tested with the same paradigm but using face stimuli, to assess the specificity of the reported effects to the musical domain. Indeed, brain imaging studies in healthy participants have demonstrated shared brain networks for emotion perception with music, vocalization and also face material, especially for fear recognition (Aubé, Angulo-Perkins, Peretz, Concha, & Armony, 2015; Koelsch et al., 2013; Paquette et al., 2018). Thus impairments of facial and vocal emotion perception might cooccur with impaired musical emotion perception.

The aim of the present study was to investigate musical emotion recognition and its perceived intensity after unilateral brain damage, in particular to determine the potential effect of lesion side on emotion perception. In contrast to previous group studies investigating musical emotions in brain-damaged patients, we did not restrict the patient selection to lesions encompassing mesial temporal structures (including amygdala or parahippocampus) (Dellacherie et al., 2011; Frühholz, Trost, & Grandjean, 2014; Gosselin et al., 2006, 2011), but included patients with a large variability of lesion locations aiming for a wider conclusion about the link between lesion side and emotion perception. We compared

the recognition of musical emotions and their rated intensity in RBD patients, LBD patients, and healthy comparison participants. To tease apart general emotion recognition deficits from specific auditory or musical deficits, we also used a facial emotion recognition task with its subsequent intensity ratings. Music perception abilities were also assessed to analyse their potential contribution and/or dissociation to musical emotion perception.

2. Materials and methods

2.1. Participants

Thirty-two brain-damaged patients and 28 healthy comparison participants were included in the study (Table 1). Thirty-four participants were recruited in Lyon and its surroundings (France), and 26 participants in Iowa (USA). Inclusion criteria for patients were the presence of a focal unilateral brain damage involving the cortex, without prior psychiatric disease, severe cognitive disorder, severe hearing or visual loss. All patients were tested in the chronic phase of their condition.

(more than 3 months after lesion onset). In total, 16 left brain-damaged patients (eleven from France, five from Iowa) and 16 right brain-damaged patients (ten from France, six from Iowa) were included. The 21 French patients were recruited among the patients of the stroke unit of the neurological hospital in Lyon, France. They presented a unilateral ischemic stroke in the right or left middle cerebral artery territory, confirmed by MRI. The 11 patients from Iowa (USA) presented focal brain damage due to vascular lesions ($n = 7$, including four in the territory of the middle cerebral artery, one in the anterior cerebral artery, one in the internal carotid artery, and one in the vertebral artery), surgical resection of a frontal tumor ($n = 1$), temporal lobectomy for epilepsy relief ($n = 3$). They all (except one) underwent a high resolution MRI to localize their lesions (see Table 2). Thirteen healthy comparisons were recruited in France, and fifteen healthy comparisons were recruited in the USA. They were matched to patients for age, gender, education level, and music training. Study procedures were approved by the appropriate ethics committee on both sites and participants were paid for their participation. All participants' consent was obtained according to the Declaration of Helsinki.

2.2. Neuropsychological assessment

Prior to the main experiment, all participants were tested with an audiometry, the Montreal Battery of Evaluation of Amusia (MBEA) (Peretz et al., 2003) to diagnose amusia, and a Pitch Discrimination Threshold (PDT) test (Tillmann et al., 2009). A participant was considered as amusic if he/she had a global MBEA score below 22.4/30 for participants under 60 years and 21.6/30 for participants aged over sixty years (see Table 1) (http://www.brams.umontreal.ca/plab/publications/article/57#extras) (Peretz et al., 2003).

To assess general cognitive abilities of patients, neuropsychological measures were collected before the testing session (Tables S1 & S2). Different, though globally equivalent neuropsychological tests were used in the two recruitment sites (France and Iowa). To test general cognitive functioning, French patients underwent the Mini Mental State Examination (MMSE) (Folstein, Folstein, & McHugh, 1975), and the American patients underwent the WAIS-IV (Wechsler Adult Intelligence Scale) (Hartman, 2009) for full-scale IQ (we also report sub-scores for working memory, WMI, and processing speed, PSI), the WCST (Wisconsin Card Sorting Task, Nelson, 1976) for perseverative errors (PE) and categories completed (CAT). To test verbal abilities, the French patients underwent lexical and categorical verbal fluencies, and the Montreal Evaluation of Communication (MEC) for the comprehension of linguistic prosody and emotional prosody, and the American patients were tested with an auditory-verbal learning test (AVLT), the Boston Naming Test (BNT, Kaplan, Goodglass, Weintraub, & Goodglass, 1983), and the Controlled Oral Word Association (COWA, Loonstra, Tarlow, & Sellers, 2001). The French patients also were administrated a depression scale test (Hamilton, 1960).

2.3. Stimuli

Forty musical excerpts were selected from the Western classical repertoire (Table S3). All excerpts were orchestrated instrumental stimuli, without voice, lasted 20 s, and were aimed to be representative of four emotions in real recordings (see Bigand, Filipic, & Lalitte, 2005; Filipic, Tillmann, & Bigand, 2010; Lévêque et al., 2018; Liégeois-Chauvel et al., 2014). In this selection of stimuli, ten excerpts related to joy (e.g., an excerpt from Beethoven's Piano, sonata 32, mvt 2), ten to sadness (e.g., an excerpt from Shostakovitch's Symphony 15, Adagio), ten to fear/anger (e.g., an excerpt from Chopin's Prelude, op.28, no.22), ten to serenity (e.g., an excerpt from Scarlatti's Sonata A for Harpsichord). Thus, there were two positive valence emotion categories and two negative valence emotion categories, with two high arousal emotion categories and two low arousal emotion categories.

For the visual task, forty photos of faces were selected from Ekman and Friesen (1976) (Lévêque et al., 2018). All photos were in black and white. They appeared on the screen for two seconds. To match the musical material, ten faces were related to joy, ten to sadness, ten to fear, and ten were emotionally neutral, as in Hirel et al. (2014) and Lévêque et al. (2018). Neutrality was used instead of serenity because serenity is difficult to recognize on a face.

2.4. Procedure

In each trial, participants listened to or watched a stimulus and were then asked to select the recognized emotion from four options (joy, serenity (music)/neutral (faces), sadness, fear/anger). During the tasks, only the word "fear" appeared on the screen. However, participants were informed at the beginning of the experiment that this category in the musical task corresponded to anger and fear. Indeed, anger and fear can be evoked by the same musical excerpts depending on perspective taken (see Hirel et al., 2014; Johnsen, Tranel,

Table 1 – Demographic data of participants. Standard deviations are indicated in parentheses. Group comparisons use ANOVAs with group (Comparisons, RBD patients, LBD patients) as between-participants factor, except for sex ratio and laterality where a Chi2 test was used. MBEA (Montreal Battery for the Evaluation of Amusia, Peretz, Champod, & Hyde, 2003) score = average score of the six subtests (scale, contour, interval, rhythm, meter, memory), significant difference between groups (in bold): LBD patients have significantly lower MBEA scores compared to healthy comparisons ($p = .022$) according to a Fisher-LSD post-hoc test. PDT: Pitch Discrimination Threshold (Tillmann, Schulze, & Foxton, 2009).

	HEALTHY COMPARISONS (N = 28)	RBD PATIENTS (N = 16)	LBD PATIENTS (N = 16)	P-VALUE (GROUP COMPARISON)
Sex ratio (M/F)	11/17	6/10	10/6	.26
Age (years)	58.3 (±9.9)	56 (±10.8)	67,8 (±11.7)	.21
*Laterality**	2L 24R	1L 15R	1L 15R	.98
Education (years)	14.5 (±3.4)	12.2 (±3.7)	12.9 (±3.5)	.15
*Musical education** (years)*	2 (±3.4)	.8 (±2.3)	5.6 (±14)	.24
Time since stroke (months)	NA	30.6 (±39.3)	67.4 (±78.6)	.19 (RBD vs. LBD)
Lesion size (mL)	NA	15.4 (±17.9)	21.2 (±18.4)	.55 (RBD vs. LBD)
MBEA score (max. score = 30)	25.2 (±2.1)	24 (±2.8)	23.3 (±3)	**.04**
*PDT*** (semi-tones)*	.74 (±.92)	1.31 (±1.25)	1.78 (±2.6)	.13

*Missing data for 2 healthy comparisons.
**Missing data for 5 healthy comparisons and 5 patients.
***Missing data for 6 patients.

Lutgendorf, & Adolphs, 2009; Lévêque et al., 2018). After having given their response, they were asked to rate the intensity of the emotion evoked by the musical excerpt or the face from 1 (not intense) to 5 (very intense), except for face stimuli judged as neutral. After the intensity rating response, the following stimulus was automatically played after a variable delay of 2500 ms on average (ranging from 2000 to 3000 ms). The stimuli were presented in two blocks: music in one and faces in another. The presentation order of the two blocks was counterbalanced across participants. The participant was allowed taking a small break between the two blocks. Within a block, the presentation order of the stimuli was randomized for each participant, with the constraint that a given emotion cannot be presented more than three times in a row. For both blocks (music and faces), participants were not asked to distinguish between felt and perceived emotion. Indeed, it was shown that this distinction can be complex to perform (Niedenthal, 2007; Scherer, 2004). Presentation software (Neurobehavioral systems, Albany, CA, USA) was used to present the stimuli to the participants and to record responses on a keyboard. The duration of the experiment was 20 min.

2.5. *Data analyses*

For each participant and emotion, separately for musical excerpts and faces, the percentages of correct responses (categorization score) and the average ratings of intensity for correctly categorized trials were calculated. Each dependent variable was analyzed with a 3 × 4 ANOVA with Group (LBD patients vs. RBD patients vs. comparison participants) as the between-participants factor and Emotion (Joy, Sadness, Fear, Serenity/Neutral) as the within-participant factor. For intensity ratings for facial emotions, the factor Emotion had only three levels (Joy, Sadness, and Fear), as intensity ratings were not performed for neutral stimuli. The Greenhouse-Geisser correction was applied if appropriate and corrected degrees of freedom are reported. We calculated Pearson-correlation between categorization scores and MBEA scores within each participant group (RBD, LBD, comparisons) and over the three groups. Similarly, we calculated Pearson-correlation between categorization scores and the PDT within each participant group (RBD, LBD, comparisons) and over the three groups, even though PDT data were missing for six participants (3 RBD and 3 LBD patients).

We run an additional ANOVAs for music material on categorization scores and intensity ratings with MBEA score as a covariate, to further investigate a possible link between musical perception and memory abilities (as measured in the MBEA) and emotional processing in the three groups of participants.

As the music material had been constructed in France, we also tested for potential cross-cultural differences between participants by analyzing the data of comparison participants with a 2 × 4 ANOVA with Site (France vs. USA) as a between-participants factor and Emotion (Joy, Sadness, Fear, Serenity/Neutral) as the within-participant factor, for recognition performance and intensity ratings of music and for recognition performance of face material respectively. For intensity ratings of face material, a 2 × 3 ANOVA was performed as the factor Emotion did not include Neutrality.

To test for potential effects of slightly different patient recruitment criteria on the two sites (only middle cerebral artery stroke patients were recruited in France, whereas patients with more diverse lesion etiologies were recruited in the USA), we analyzed the patient data of each dependent variable with a 2 × 2 × 4 (or 2 × 2 × 3) ANOVA with Site (France vs. USA) and Lesion Laterality (RBD vs. LBD) as between-participants factors, and Emotion (Joy, Sadness, Fear, and Serenity/Neutral where appropriate) as the within-participant factor.

For all analyses, post-hoc analyses for significant effects or interactions were carried out using Fisher LSD tests.

Individual patient data for musical excerpts and faces (percentages of correct responses and average intensity ratings for

Table 2 – Individual data on lesion localization, correct categorizations and intensity ratings of music and faces, and MBEA scores. F1–F21: French patients (F11 is described in detail in Hirel et al., 2014), A1-A11: American patients. T = temporal, F = frontal, P = parietal, I = insula, O = occipital, BG = basal ganglia. % Corr: mean correct categorization. Int.: mean intensity ratings. Data below or above the cutoffs are in bold.

PATIENTS	LESION SIDE	LESION LOCALISATION						MUSIC		FACES		MEAN MBEA (MAX=30)
		T	F	P	I	O	BG	% CORR.	INT.	% CORR.	INT	
F1	Right				x		x	62.5	3.27	**70**	**1.90**	22.5
F2	Right	x		x	x			77.5	3.82	90	4.06	24.17
F3	Right	x		x	x			75	4.18	85	3.43	27
F4	Right	x	x		x			**55**	3.67	85	**4.47**	24.17
F5	Right			x	x			77.5	3.55	90	4.13	24.5
F6	Right	x						80	3.33	90	3.07	27.5
F7	Right	x	x		x			67.5	3.31	87.5	3.40	26.83
F8	Right			x				82.5	4	**70**	3.21	23.5
F9	Right		x	x				75	4.42	80	3.33	22.67
F10	Right			x	x			57.5	3.43	77.5	**2.40**	23.33
F11	Right	x						77.5	**1.48**	80	3.3	**21.5**
A1	Right	x						82.5	2.42	95	3.89	**19.17**
A2	Right						x	72.5	3.08	85	3.7	23
A3	Right						x	65	2.52	**67.5**	3.05	**21**
A4	Right		x					92.5	3.37	97.5	3.47	28.67
A5	Right	Missing data						60	3.73	95	3.63	**21.33**
F12	Left	x		x	x			**52.5**	2.42	95	3.43	**18.5**
F13	Left	x		x	x			85	3.48	92.5	3.90	24.17
F14	Left		x		x			65	3.11	82.5	3.45	26.67
F15	Left	x		x	x			72.5	3.44	85	3.86	22.83
F16	Left		x		x			72.5	3.33	82.5	3.33	25.33
F17	Left			x	x			**42.5**	3.56	82.5	3.36	22
F18	Left		x	x	x			**50**	4.34	80	**4.49**	**17.67**
F19	Left		x		x			62.5	**4.96**	80	3.94	**18.67**
F20	Left	x						67.5	3.17	87.5	3.50	26.17
F21	Left				x			85	3.69	82.5	3.86	26.17
A6	Left	x						**50**	3.56	92.5	3.91	**21.17**
A7	Left		x		x			82.5	2.87	90	3.70	24
A8	Left			x				72.5	4.29	87.5	3.93	25.5
A9	Left					x		70	3	95	2.92	22.5
A10	Left	x						**55**	3.49	85	**1.90**	26
A11	Left					x		77.5	3.42	87.5	2.51	26.67
TOTAL	Right	7	4	6	7	0	3					
TOTAL	Left	6	5	6	10	2	0					
COMPARISONS MEAN								78.92	3.56	88.39	3.44	
HIGH CUTOFF									4.86		4.38	
LOW CUTOFF								55.53	2.26	74.04	2.50	22.4 (<60 years) 21.6 (>60 years)

correctly categorized trials) were also analyzed. For percentages of correct responses, individual data were compared to a cutoff score corresponding to the comparisons' mean minus two standard deviations. For average intensity ratings, individual data were compared to a cutoff score corresponding to the comparisons' mean minus two standard deviations (low cutoff) and to a cutoff score corresponding to the comparisons' mean plus two standard deviations (high cutoff).

2.6. *Transparency and openness promotion of the study*

We report in the 'Participants' section how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

We were not the owners of most of the stimuli we used in the study. Readers seeking access to the stimuli may contact A. Pralus to obtain the contacts of the research teams who originally created the stimuli and collaborated with us either in the present study or a previous one or have made public access already. Material and stimuli of the MBEA (Peretz et al., 2003) are accessible on https://www.peretzlab.ca/knowledge_transfer/. The Pitch Discrimination test has been developed by Jessica Foxton and used in the following publications or our team: Hirel et al., 2014; Lévêque et al., 2018; Pralus et al., 2019; Tillmann et al., 2009. Stimuli from the MMSE test are hold by the Folstein group (Folstein et al., 1975). Instructions for the WAIS examination are commercialized by the Wechsler group (Hartman, 2009). Stimuli from the MEC protocol are commercialized by Ortho Edition (Joanette et al., 2004. Protocole Montréal d'évaluation de la communication (MEC). Isbergues, France: Ortho-Edition). The stimuli of the Boston Naming Test are commercialized by Pearson Clinical (Kaplan et al., 1983. Boston Naming Test-Second Edition). The stimuli of Controlled Oral Word Association are owned by the Psychological

Assessment Resources (Loonstra et al., 2001. PAR, https://www4.parinc.com/Products/PermissionsAndLicensing.aspx). The depression scale test is available as an appendix in the original research article (Hamilton, 1960). Musical stimuli for the emotion categorization test have been selected by Emmanuel Bigand and Philippe Lalitte (University of Burgundy, LEAD–CNRS 5022, Dijon, France), and used in the following collaborative publication: Leveque et al. (2018). Copyright for face stimuli (Ekman & Friesen, 1976) is held by Paul Ekman Group.

The conditions of our ethics approval do not permit public archiving of anonymized study data. Readers seeking access to the data should contact A. Pralus. Access will be granted to named individuals in accordance with ethical procedures governing the reuse of clinical data, including completion of a formal data sharing agreement and approval of the local ethics committee.

No part of the study procedures was pre-registered prior to the research being conducted.

3. Results

3.1. Neuropsychological data

Tables S1 and S2 show results of the neuropsychological assessment for patients from both recruitment sites. For general cognitive functioning, only three French LBD patients were slightly cognitively impaired (MMSE scores between 23 and 24), no American patient had an impairment (all WAIS scores between 70 and 130), except one American RBD patient who was below the norms of the WCST-PE (but not impaired for the WCST-CAT). For verbal abilities in French patients, two RBD and one LBD patients had a deficit for lexical fluencies (scores lower than 8.09, age-adjusted cutoff) and one RBD patient had a deficit for categorical fluencies (score lower than 20.46, age-adjusted cutoff), no patient was below the norm for emotional and linguistic prosody (MEC battery). For verbal abilities in American patients, only one RBD patient had a deficit for AVLT (score lower than 6.8), no patient had a deficit for BNT and COWA. For the depression scale (only French patients were tested), 6 RBD and 7 LBD patients had scores below the norm (scores lower than 7).

Overall, these neuropsychological tests revealed that the patients included in the study were not severely cognitively impaired, and potential deficits observed in our paradigm would most likely not be due to a more general deficit of cognition. The depression scale revealed that some patients were not in the norm (6 RBD and 7 LBD patients), which is common in brain-damaged patients. However, most importantly, depression scores were similar in LBD and RBD patients, thus depression scores cannot explain potential group differences between the two patient groups in the other tasks.

Regarding music perception abilities, MBEA scores revealed that two healthy comparison participants and eight patients (4 RBD and 4 LBD) were amusic (MBEA scores below the cutoff according to their age). An ANOVA with the factor group (LBD patients, RBD patients, comparisons) (see Table 1) revealed a significant main effect ($F(2, 57) = 3.38$, $p = .04$), with only the LBD patients having lower MBEA scores than comparisons ($p = .022$, other $p > .064$). For PDT, the ANOVA did not reveal a significant main effect of group ($F(2, 51) = 2.11$, $p = .13$).

Finally, the patterns of lesions observed for the patients in cortical and subcortical regions were variable across patients, with overall similar localizations of lesions for LBD and RBD patients (Table 2, Fig. 1).

3.2. Musical emotions

Emotion categorization (Fig. 2A). The main effect of group was significant ($F(2, 58) = 5.02$, $p = .0097$, partial $\eta^2 = .15$). LBD patients had significantly lower scores than comparisons ($p = .0028$), but no significant difference was found between RBD patients and comparisons ($p = .09$) or between the two patient groups ($p = .23$). The main effect of emotion was Significant ($F(2.74, 159.02) = 20.195$, $\epsilon = .91$, $p < .001$, partial $\eta^2 = .26$), with Joy and Fear being each better recognized than Sadness or Serenity (all $p < .001$). The interaction of group with emotion was not significant ($F(5.48, 159.02) = .76$, $\epsilon = .91$, $p = .59$, partial $\eta^2 = .026$).

The correlation between correct emotion categorizations and MBEA scores was significant when pooling data across the three groups ($r(58) = -.54$, $p < .001$). A significant correlation was found for the group of LBD patients ($r(14) = .57$, $p = .022$) and for comparisons ($r(26) = .51$, $p = .006$), but not for RBD patients ($r(14) = .35$, $p = .19$) (Fig. 3A). The correlation between correct emotion categorizations and PDT was significant over the three groups ($r(52) = -.3$, $p = .027$). No significant correlation was found for RBD patients ($r(14) = -.47$, $p = .1$), and for LBD patients ($r(14) = .025$, $p = .94$), but the correlation was significant for comparisons ($r(26) = -.5$, $p = .007$) (Fig. 3B).

Additional analysis with MBEA covariate.[2] The main effect of group was still nearly significant ($F(2, 56) = 3$, $p = .058$, partial $\eta^2 = .097$). LBD patients had significantly lower scores than comparisons ($p = .05$), but no significant difference was found between RBD patients and comparisons ($p = .36$) or between the two patient groups ($p = .32$). The main effect of emotion was no longer significant ($F(2.77, 155.01) = 1.19$, $\epsilon = .92$, $p = .32$, partial $\eta^2 = .021$). The interaction of group with emotion was not significant ($F(5.54, 155.01) = .79$, $\epsilon = .92$, $p = .58$, partial $\eta^2 = .026$). The main effect of MBEA was significant ($F(1, 56) = 15.3$, $p < .001$, partial $\eta^2 = .215$). The interaction of MBEA with emotion was not significant ($F(2.77, 155.01) = 1.17$, $\epsilon = .92$, $p = .32$, partial $\eta^2 = .02$).

Intensity ratings for correct responses (Fig. 2B). The entire range (from 1 to 5) of intensity ratings was covered by the participants, showing that over the groups, the subjective scale was fully used when rating the stimuli. One RBD patient was excluded from the analysis of intensity ratings because for sad musical excerpts, recognition performance was 0%.

The main effect of group was not significant ($F(2, 57) = .52$, $p = .60$, partial $\eta^2 = .018$). The main effect of emotion was significant ($F(2.63, 149.64) = 4.99$, $\epsilon = .88$, $p = .0024$, partial $\eta^2 = .08$), with Joy rated as more intense than Sadness, Fear, and Serenity

[2] We performed an additional analysis with PDT as a covariate on 54 participants (6 PDT scores were missing) on categorization scores of musical emotions. This analysis gave similar pattern of results as in the main analysis, and no effect or interaction involving PDT was significant.

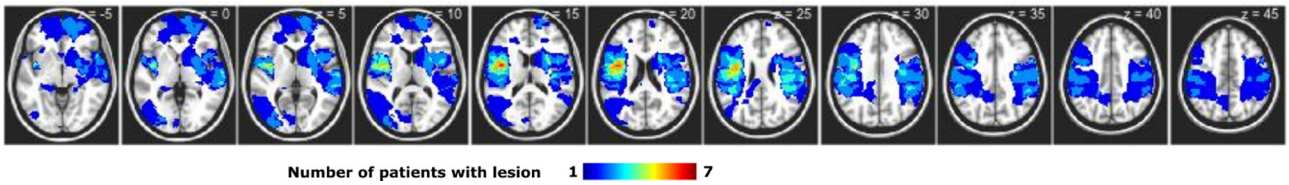

Fig. 1 – Localization of patients' lesions. Overlay of lesions in the patient groups revealed a quite distributed localizations of lesions with similar patterns in left and right hemisphere. Missing data: 1 RBD and 2 LBD patients.

($p < .001$, $p = .011$, and $p = .018$ respectively). The interaction of group with emotion was significant (F (5.25, 149.64) = 2.46, $\epsilon = .88$, $p = .026$, partial $\eta^2 = .079$). RBD patients rated Serenity as more intense than Sadness and Fear (all $p < .003$), whereas no such pattern was observed in the two other groups ($p > .09$). Comparisons rated Joy higher than Sadness and Serenity ($p = .009$ and $p = .004$, respectively). RBD patients had lower intensity ratings for Fear compared to comparisons ($p = .037$), and marginally lower intensity ratings for Fear compared to LBD patients ($p = .10$) (all other $p > .13$).[3]

The correlation between intensity ratings and MBEA scores was not significant over the three groups (r (58) = -.10, $p = .44$) nor in any of the three groups: for RBD patients (r (14) = .37, $p = .16$), for LBD patients (r (14) = -.26, $p = .33$), and for comparisons (r (26) = .10, $p = .61$) (Fig. 3C). The correlation between the intensity ratings and the PDT was not significant over the three groups (r (52) = .14, $p = .33$) nor in any of the three groups: for RBD patients (r (14) = .13, $p = .67$), for LBD patients (r (14) = .45, $p = .12$), and for comparisons (r (26) = -.074, $p = .71$) (Fig. 3D).

Additional analysis with MBEA covariate.[4] The main effect of group was not significant (F (2, 55) = .413, $p = .66$, partial $\eta^2 = .015$). The main effect of emotion was no longer significant (F (2.67, 146.56) = 1.38, $\epsilon = .89$, $p = .25$, partial $\eta^2 = .024$). The interaction of group with emotion was significant (F (4.29, 146.56) = 2.48, $\epsilon = .89$, $p = .046$, partial $\eta^2 = .076$). RBD patients rated Serenity as more intense than Sadness and Fear (all $p < .003$), whereas no such pattern was observed in the two other groups ($p > .3$). Comparisons rated Joy higher than Sadness and Serenity ($p = .009$ and $p = .004$, respectively). RBD patients had lower intensity ratings for Fear compared to comparisons ($p = .037$), and marginally lower intensity ratings for Fear compared to LBD patients ($p = .10$) (all other $p > .13$). The main effect of MBEA was not significant (F (1, 55) = .16, $p = .70$, partial $\eta^2 = .003$). The interaction of MBEA with emotion was not significant (F (2.67, 146.56) = 1.48, $\epsilon = .89$, $p = .23$, partial $\eta^2 = .026$).

3.3. *Facial emotions*

Emotion categorization (Fig. 2C). The main effect of group was not significant (F (2, 58) = 1.78, $p = .18$, partial $\eta^2 = .059$). The main effect of emotion was significant (F (2.12, 120.84) = 43.09, $\epsilon = .71$, $p < .001$, partial $\eta^2 = .43$), with Joy and Fear being better recognized than Sadness and Neutrality (all $p < .001$). The interaction between group and emotion was not significant (F (4.24, 120.84) = 1.84, $\epsilon = .71$, $p = .094$, partial $\eta^2 = .061$).

Intensity ratings for correct responses (Fig. 2D). The entire range (from 1 to 5) of intensity ratings was covered by the participants, showing that over the groups, the subjective scale was fully used when rating the stimuli.

The main effect of group was not significant (F (2, 58) = .05, $p = .95$, partial $\eta^2 = .002$). The main effect of emotion was significant (F (1.97, 114.46) = 48.72, $\epsilon = .99$, $p < .001$, partial $\eta^2 = .47$), with Joy rated higher than Sadness and Fear ($p < .001$, and $p = .035$ respectively), and Fear rated higher than Sadness ($p < .001$). The interaction of group with emotion was not significant (F (3.95, 114.46) = 1.012, $\epsilon = .99$, $p = .4$, partial $\eta^2 = .034$).[5]

Data for music and faces material were also analyzed together with a 3 × 4 × 2 ANOVA for emotion categorization with Group (LBD vs RBD patients vs comparisons) as the between-participant factor and Emotion (Joy, Sadness, Fear, Neutrality/Serenity) and Task (Music vs Face) as the within-participant factors. For Intensity ratings, a 3 × 3 × 2 ANOVA was done as Neutrality with Faces material did not have intensity ratings. For correct categorization, the main effect of Task, Emotion and Group were significant ($p < .001$, $p < .001$ and $p = .009$ respectively) as the interactions between Task and Group ($p = .021$), and between Task and Emotion ($p = .017$). Post-hoc revealed that the three participant groups had higher scores for faces than music (all $p < .006$), for music material, comparisons had higher scores that LBD patients ($p = .001$). Post-hoc revealed significant higher scores for faces material compared to music material for Joy, neutrality/Serenity and Fear (all $p < .001$). For intensity ratings, the main effect of Emotion was significant ($p < .001$), as well as the interaction of Task and Emotion ($p < .001$). The triple interaction of Task, Group and Emotion was nearly significant ($p = .057$). For faces material, post-hoc revealed that Sadness was rated lower than Fear and Joy for the three groups (all $p < .04$).

[3] An additional ANOVA was performed on all intensity ratings (not only for intensity ratings of the correctly categorized trials). This showed similar results, notably with the main effect of Emotion being significant ($p < .001$) and the interaction between Group and Emotion falling just short of significance ($p = .059$).

[4] We performed an additional analysis with PDT as a covariate on 54 participants (6 PDT scores were missing) on intensity ratings of musical emotions. This analysis gave similar pattern of results as in the main analysis, and no effect or interaction involving PDT was significant.

[5] An additional ANOVA was performed on all the intensity ratings (not only for intensity ratings of the correctly categorized trials). This showed similar results, notably with the main effect of Emotion being significant ($p < .001$).

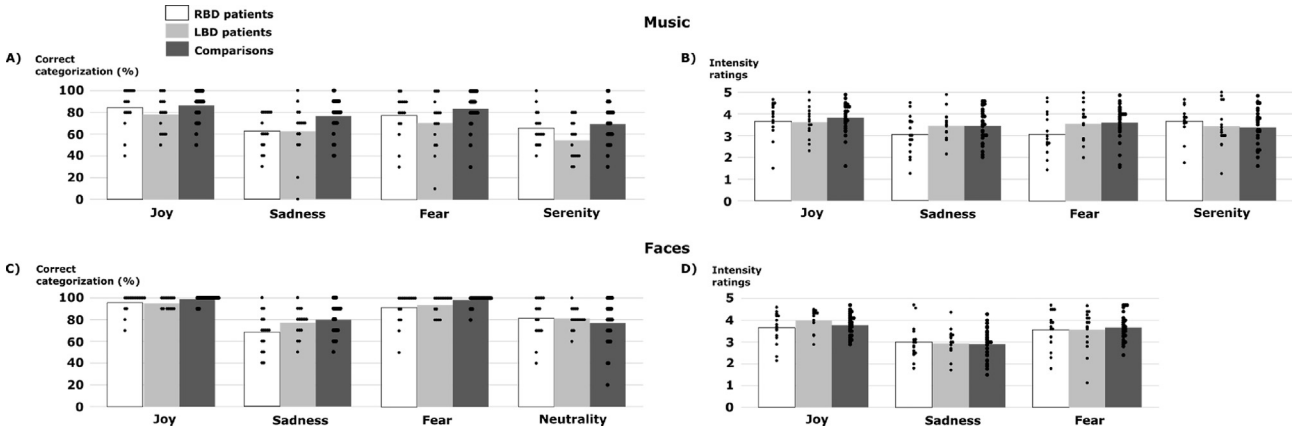

Fig. 2 – Percentage of correct emotion categorization and intensity ratings for music (A and B) and face (C and D) materials in the three groups of participants (RBD patients, LBD patients, comparisons). Bars represent the group means and dots correspond to individual data points. LBD patients had significantly lower correct categorization scores than comparison participants for music material (Panel A). RBD patients had lower intensity ratings for negative emotions in music, a pattern that was not observed in the other two groups (Panel B). All groups showed similar correct categorizations and intensity ratings for faces (Panels C & D).

For music material, post-hoc revealed that Joy was rated higher than Sadness for comparisons and RBD patients (all $p < .038$), interestingly RBD patients also rated Fear lower than Joy ($p = .028$), no such pattern was observed in the other two groups.

3.4. *Testing for potential cross-cultural differences and patient recruitment differences in France and the USA*

3.4.1. *Cross-cultural differences in comparisons participants*

Only effects and interactions involving the factor recruitment site are reported below, effects of emotion mirror the results of the main analyses.

Musical emotion categorization (Fig. 4A). The main effect of site ($F(1, 26) = .71$, $p = .40$, partial $\eta^2 = .026$) was not significant, neither its interaction with emotion ($F(2.42, 62.82) = 1.76$, $\epsilon = .81$, $p = .17$, partial $\eta^2 = .063$).

Musical emotion intensity ratings (Fig. 4B). The main effect of site ($F(1, 26) = 1.15$, $p = .29$, partial $\eta^2 = .042$) was not significant, neither its interaction with emotion ($F(2.36, 61.25) = 1.55$, $\epsilon = .79$, $p = .22$, partial $\eta^2 = .056$).

Face emotion categorization (Fig. 4C). The main effect of site ($F(1,26) = 3.55$, $p = .071$, partial $\eta^2 = .12$) did not reach significance, but suggests a slight tendency of Americans comparisons to have better recognition scores compared to French comparisons. The interaction between site and emotion was not significant ($F(1.86, 48.42) = .83$, $\epsilon = .62$, $p = .43$, partial $\eta^2 = .031$).

Face emotion intensity ratings (Fig. 4D). The main effect of site ($F(1, 26) = .11$, $p = .74$, partial $\eta^2 = .0043$) was not significant, neither its interaction with emotion ($F(1.83, 47.58) = .34$, $\epsilon = .92$, $p = .70$, partial $\eta^2 = .013$).

3.4.2. *Patient recruitment across the two sites*

Only effects and interactions involving the site factor are reported below, effects and interactions of emotion and group mirror the results of the main analyses.

Musical emotion categorization (Fig. 5A). The main effect of site was not significant ($F(1, 28) = .34$, $p = .57$, partial $\eta^2 = .012$), neither its interaction with emotion ($F(2.75, 77.03) = .49$, $\epsilon = .92$, $p = .67$, partial $\eta^2 = .017$), nor its interaction with lesion-side ($F(1.28) = .0029$, $p = .96$, partial $\eta^2 < .001$). The three-way interaction of lesion-side, emotion and site was not significant ($F(2.75, 77.03) = 2.1$, $\epsilon = .92$, $p = .11$, partial $\eta^2 = .07$).

Musical emotion intensity ratings (Fig. 5B). The main effect of site was not significant ($F(1, 27) = 1.27$, $p = .27$, partial $\eta^2 = .045$), neither its interaction with emotion ($F(2.77, 74.71) = 2.46$, $\epsilon = .92$, $p = .074$, partial $\eta^2 = .083$), nor its interaction with lesion-side ($F(1, 27) = .048$, $p = .49$, partial $\eta^2 = .018$). The three-way interaction of lesion-side, emotion and site was not significant ($F(2.77, 74.71) = .78$, $\epsilon = .92$, $p = .50$, partial $\eta^2 = .028$). The marginal interaction between the effect of site and emotion revealed a slight tendency of French patients to rate higher the intensity of Fear stimuli compared to American patients.

Face emotion categorization (Fig. 5C). The main effect of site was not significant ($F(1, 28) = 3.61$, $p = .068$, partial $\eta^2 = .11$), neither its interaction with emotion ($F(2.25, 63.08) = 1.41$, $\epsilon = .75$, $p = .25$, partial $\eta^2 = .048$), nor its interaction with lesion-side ($F(1.28) = .044$, $p = .84$, partial $\eta^2 = .002$). The three-way interaction of lesion-side, emotion and site was not significant ($F(2.25, 63.08) = .18$, $\epsilon = .75$, $p = .91$, partial $\eta^2 = .006$).

Face emotion intensity ratings (Fig. 5D). The main effect of site was not significant ($F(1, 28) = .61$, $p = .44$, partial $\eta^2 = .019$), neither its interaction with emotion ($F(1.96, 54.85) = .87$, $\epsilon = .98$, $p = .42$, partial $\eta^2 = .030$), nor its interaction with lesion-side ($F(1.28) = 2.86$, $p = .1$, partial $\eta^2 = .093$). The three-way interaction of lesion-side, emotion and site was not significant ($F(1.96, 54.85) = 1.47$, $\epsilon = .98$, $p = .24$, partial $\eta^2 = .050$).

According to these results, potential differences of patient recruitment across site cannot be considered as a major source of variability or groups differences observed in our study. It seems that even though the recruitment of patients

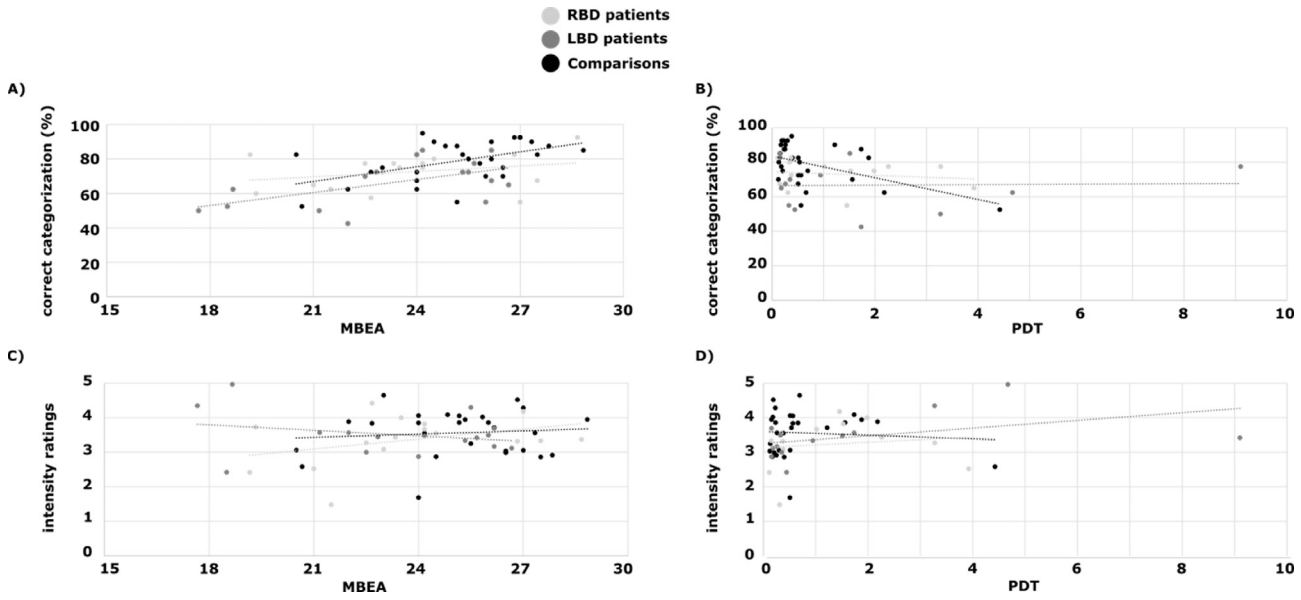

Fig. 3 – Correlations between MBEA and PDT scores and correct categorizations and intensity ratings of music material in the three groups of participants (RBD patients, LBD patients and comparisons). Significant correlation between MBEA score and correct categorization (A) was found for LBD patients ($r(14) = .57$, $p = .022$) and for comparisons ($r(26) = .51$, $p = .006$). Significant correlation between PDT and correct categorization (B) was found for comparisons ($r(26) = -.5$, $p = .007$). No significant correlation was found between intensity ratings and MBEA score (C) and PDT (D), respectively.

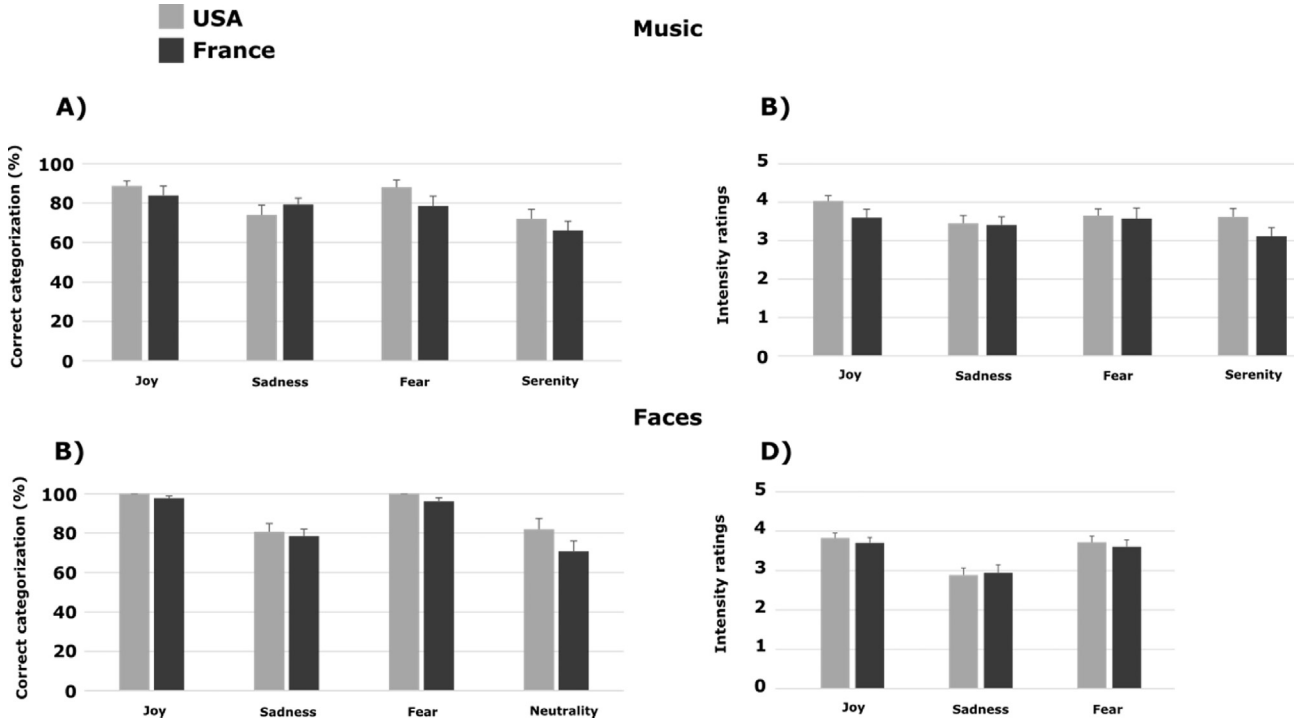

Fig. 4 – Percentages of correct categorization and intensity ratings of comparisons from France and USA, with music (A and B) and face (C and D) materials. No difference was observed between comparisons s from France and USA with both materials, confirming that cross-cultural differences did not influence significantly the results. Error bars indicate the standard error of the mean.

was conducted in two countries, with slightly different inclusion criteria, similar patterns of results were observed on both sites. In conclusion, the results observed with facial and musical emotions are observed across the two western cultures and reflect potential deficits in patients compared to comparisons.

4. Discussion

The present study investigated musical and facial emotion processing after unilateral brain damage. Participants had to categorize the emotion of musical excerpts or faces and rate the intensity of the emotion. Performance in the musical emotion recognition test was significantly lower in LBD patients than comparison participants. RBD patients were not impaired for musical emotion recognition, but rated the emotional intensity of music lower for sadness and fear than for joy and serenity; this difference in intensity ratings was not observed for LBD patients and comparisons. There was no difference for facial emotions (categorization or intensity) between patients and comparison participants, suggesting that the patient groups did not present a general emotion deficit or alteration.

4.1. *Deficits of musical emotion recognition after unilateral brain damage*

Recognition scores of musical emotions revealed a significant deficit in LBD patients compared to comparisons. No significant deficit was observed in RBD patients; note, however, that their performance was numerically in-between that of comparisons and LBD patients. Previous case reports in brain-damaged patients already reported deficits in music emotion recognition associated to various lesions sites (Gosselin et al., 2011, 2007; Griffiths et al., 2004), but no clear association between the lesion site and the deficits has been made. Hence, previous group studies have investigated musical emotion recognition in brain-damaged patients, but focusing up to now only on lesion locations in the mesio-temporal area. The findings of Khalfa et al. (2007, 2008) were in line with our results, notably with stronger impairment of LBD patients than in RBD patients. Note however the slightly different patterns across studies, with one study showing deficit of the LBD patients for sadness and happiness (Khalfa et al., 2008), but another for sadness and anger (Khalfa et al., 2007), and here a more distributed deficit across all emotions in LBD patients. In contrast, Jafari et al. (2017) observed stronger impairment for RBD patients than LBD patients with music material, in particular for sadness and neutrality. Another group study on patients with temporal lobe resection did not find any deficit in LBD and RBD patients in comparison to comparisons for valence and arousal categorizations (Dellacherie et al., 2011). Altogether, the restriction of lesion location in the mesio-temporal area in these studies restricted conclusions. Our study extends the link between potential musical emotion perception deficits and involved brain structures by investigating more various lesion locations than previous studies. It also allows for a comparison between left and right brain damage, with a stronger deficit for emotion recognition associated to left hemisphere damage. Beyond the laterality differences observed here, there were no clear associations between the pattern of musical emotion recognition performance and individual lesion localizations (Table 2). For example, patients showing a deficit at the individual level in musical emotion categorization had a lesion in either parietal, frontal, or temporal cortex. One could argue that there were slightly more LBD patients with a lesion to the insula compared to RBD patients (10 vs 7 patients) that could have influenced the musical emotion recognition results. However, there were no clear association between insula lesion and individual deficit of musical emotion recognition as only half of the LBD patients showing individual deficit also had insula lesion, and only one RBD patient with insula lesion had individual deficit.

Differences in the duration of the used musical material might explain some of the differences observed between previous and our results. Previous studies investigating musical emotions in brain-damaged patients used shorter excerpts of music than we did. In most studies, the stimuli lasted less than 10 s on average (5 s in Dellacherie et al., 2011; 1.5 s in Jafari et al., 2017; 7 s in Khalfa et al., 2008), which limits the number of acoustic cues available to make a decision about the presented emotion. Even though these stimuli might be long enough for comparison participants to detect and identify an emotion (Bigand et al., 2005), they might be too short for patients to make the same judgement. As previously shown in individuals with congenital amusia, the duration of stimuli is essential to allow for extracting a sufficient number of acoustic cues to determine the emotion (Pralus et al., 2019). In the present study, we used musical excerpts of an average duration of 20 s aiming to put participants in the best situation to recognize the emotion. This could explain why we found no deficit in RBD patients. However, the deficit of musical emotion recognition was still present in LBD patients. These results are similar to Khalfa et al. (2007), who also used stimuli that lasted 20 s on average. Moreover, some studies used excerpts played with just one instrument (piano or violin), which could also explain the difference observed between their results and ours (Jafari et al., 2017; Khalfa et al., 2008). Here, we used orchestrated musical extracts to communicate stronger emotions with the use of ecologically valid music, and avoid the potential confound of deficits in the processing of specific timbres (see also Khalfa et al., 2007).

Deficits in musical emotion recognition in LBD patients were not linked to facial emotion recognition deficits in the present study. In contrast to previous studies on facial emotion recognition after brain damage (Borod et al., 2002; Charbonneau et al., 2003; Cheung et al., 2006; Harciarek et al., 2006), no deficit was observed here for patients on the facial task at the group level. Note however, that the facial task was

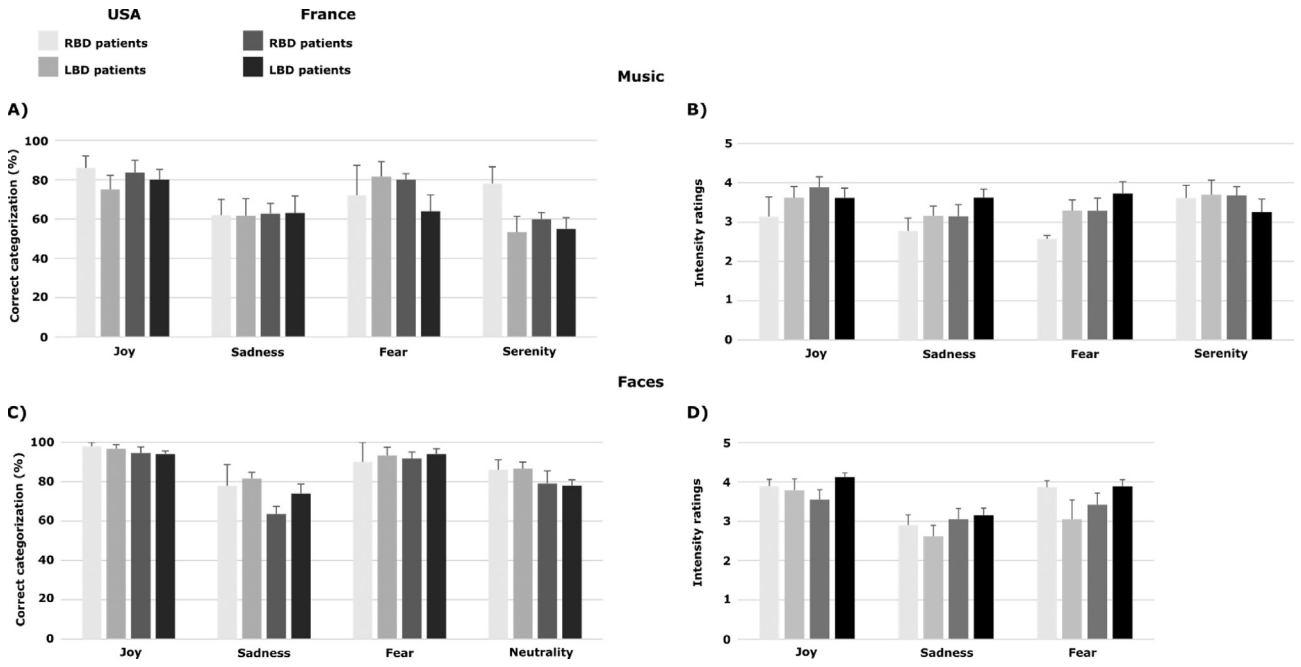

Fig. 5 – Percentages of correct categorization and intensity ratings of patients (RBD and LBD) from France and USA, with music (A and B) and face (C and D) materials. No difference was observed between patients from France and USA with both materials, confirming that selection of patients from both countries did not significantly influence the results. Error bars indicate the standard error of the mean.

easier than the musical task, as revealed by the higher scores obtained by comparison participants. This suggests that the Right Hemisphere Hypothesis previously supported by facial material (Borod, Bloom, Brickman, Nakhutina, & Curko, 2002; Charbonneau et al., 2003; Harciarek et al., 2006; Kucharska-Pietura, Phillips, Gernand, & David, 2003; Tippett et al., 2018) may be specific to facial material and not generalized to all emotions recognition. These results with facial material also confirmed that despite the depression scores below the cut-off in some patients, they did not have a general emotional deficit that could have influenced the results with music material.

Three RBD patients had a brain damage in the basal ganglia, which could have influenced the group results. Another study on facial emotion recognition showed that patients with localized basal ganglia damage performed significantly worse in recognizing negative emotions than comparisons (anger, disgust and fear) (Cheung, Lee, Yip, King, & Li, 2006). However, at the group level, we did not observe any difference between the three groups for facial emotion recognition.

4.2. *Links between musical emotion recognition and music perception*

Over the three participant groups, percentage of correct categorization of musical emotions correlated positively with the MBEA mean score. This was also the case for LBD patients and comparisons, but not for RBD patients. LBD patients had a lower MBEA mean score compared to comparisons. Moreover, when MBEA was considered in the categorization scores analysis, we demonstrated that the effect of MBEA was indeed significant, demonstrating a potential effect of the deficit of musical perception in LBD patients on musical emotion recognition results. These results of LBD patients are in agreement with a study on congenital amusia (Lévêque et al., 2018) showing that congenital amusic individuals (diagnosed by low MBEA scores) were impaired in musical emotion categorization in comparison to comparison participants. These findings reveal that some of the participants could have a global deficit in evaluating musical stimuli (Särkämö et al., 2009; Tillmann, Albouy, & Caclin, 2015). This might also reflect deficits in more general cognitive abilities required by the MBEA (Särkämö et al., 2009, 2010). Indeed, three LBD patients had also a MMSE score below the cut-off which could have influenced the MBEA results. However, this medium cognitive deficit could not be the only cause of musical emotion perception deficit as LBD patients were not impaired for facial emotion perception.

Based on the present group-level results, we can argue that cognitive and perceptual musical abilities are important for explicitly recognizing musical emotions, as the LBD patients showed decreased MBEA scores as well as deficits in musical

emotion recognition. However other parameters must be involved in recognizing musical emotions, as patients can have acquired amusia without deficit in categorization of musical emotions (see patient F11, also in Hirel et al., 2014) or participants with congenital amusia can demonstrate preserved sensitivity to emotional music (Gosselin, Paquette, & Peretz, 2015). The variety of profiles observed among the present patient sample are in keeping with the hypothesis of (at least partly) separate processes for music perception and emotion (Peretz et al., 1998; Satoh et al., 2011; Stewart, von Kriegstein, Warren, & Griffiths, 2006). Furthermore, we did not observe any link between emotion intensity ratings and perceptual musical abilities.

4.3. *A deficit of valence processing in musical emotions in RBD patients*

For the musical materials, RBD patients did not show any deficit on musical emotion recognition, but rated the emotional intensity of music lower for sadness and fear than for joy and serenity, in agreement with the valence hypothesis. This pattern of ratings was not observed in the two other groups (LBD patients and comparisons). Previous group studies on mesio-temporal lobe damaged patients also provided data in line with the validity of the valence hypothesis using a task of musical emotion recognition (Jafari et al., 2017; Khalfa et al., 2007, 2008). The present results further support this hypothesis based on patient groups with more diverse lesion locations and on intensity ratings of musical emotions.

4.4. *Clinical interest of assessing musical emotions*

In the present results, it is noteworthy that RBD patients did not show any deficit in emotion categorization, whereas they exhibited an abnormal pattern of intensity ratings of musical emotions. This pattern suggests that conceptual knowledge about emotion categories can persist even when the intensity of emotions is abnormally perceived. Intensity ratings may reflect more implicit representation of the emotion and could be linked to what emotions the listener really feels (Hirel et al., 2014; Lévêque et al., 2018). For congenital amusic participants, this paradigm has revealed a reverse pattern compared to the present study, with preserved implicit capacities to process musical emotions (i.e., with preserved intensity ratings), but impairments in the classical explicit categorization test (Lévêque et al., 2018; see also; Tillmann, Lalitte, Albouy, Caclin, & Bigand, 2016). Intensity ratings can be considered as an implicit investigation method as no verbal categorization of a given emotion and only a weak internal representation of the stimulus is necessary to provide a judgement. In the present study, intensity ratings allowed revealing deficits in patients that could not be detected with the recognition paradigm. Thus, intensity ratings, in combination with explicit recognition measures, could allow building a sensitive test to detect possible emotion perception abnormalities in clinical settings, even if a patient is unaware of this deficit (Stewart et al., 2006; Tillmann et al., 2016). Moreover, this paradigm reveals the distinction between cognitive intentional process of emotion recognition, and the emotional experience of music in unilateral brain-damaged patients, as it was already suggested in healthy participants and unilateral brain-damaged patients with facial and vocal stimuli (Abbott et al., 2013; Borod et al., 2002; Demaree et al., 2005).

5. Conclusion

The present study revealed two major patterns of potential deficits in musical emotion processing after brain damage. Our findings reveal a specific deficit for musical emotion categorization in LBD patients, whereas intensity ratings showed that right brain-damaged patients underrated negative valence emotions (compared to left brain-damaged patients and comparisons). Intensity rating data were thus compatible with the valence hypothesis, and the overall data pattern refines the distinction between the roles of the two hemispheres: the right hemisphere seems to be important to experience emotions, in particular negative emotions, whereas the left hemisphere seems to be more strongly involved in recognizing emotions at an explicit level. This hemispheric differentiation extends beyond the mesio-temporal structures of the brain, which were the focus in previous musical emotion studies with brain-damaged patients.

Author contribution

Agathe Pralus: Formal analysis, Investigation, Writing-Original draft
Amy Belfi: Investigation, Conceptualization
Catherine Hirel Investigation, Conceptualization
Yohana Lévêque: Resources
Lesly Fornoni: Investigation
Emmanuel Bigand: Resources
Julien Jung: Resources
Daniel Tranel: Supervision, Funding acquisition
Norbert Nighoghossian: Resources
Barbara Tillmann: Supervision, Funding acquisition, Project administration
Anne Caclin: Supervision, Funding acquisition, Project administration

Declaration of Competing Interest

The authors report no competing interests.

Acknowledgments

We thank the patients and comparison participants for their time and participation to the study. We thank Roxane Hoyer for help with the analyses of neuropsychological data.

This work was supported by grants from Agence Nationale de la Recherche of the French Ministry of Research ANR-11-BSH2-001-01 to BT and AC, and ANR-14-CE30-0001-01 to AC.

CH was funded by an "Année Recherche" grant from "ARS (Agence Régionale de Santé) Rhône-Alpes". This work was conducted in the framework of the LABEX CELYA ("Centre Lyonnais d'Acoustique", ANR-10-LABX-0060) and of the LabEx Cortex ("Construction, Function and Cognitive Function and Rehabilitation of the Cortex", ANR-11-LABX-0042) of Université de Lyon, within the program "Investissements d'avenir" (ANR-16-IDEX-0005) operated by the French National Research Agency.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2020.05.015.

REFERENCES

Abbott, J. D., Cumming, G., Fidler, F., & Lindell, A. K. (2013). The perception of positive and negative facial expressions in unilateral brain-damaged patients: A meta-analysis. *Laterality, 18*(4), 437–459. https://doi.org/10.1080/1357650X.2012.703206.

Adolphs, R., Jansari, A., & Tranel, D. (2001). Hemispheric perception of emotional valence from facial expressions. *Neuropsychology, 15*(4), 516–524.

Adolphs, R., Tranel, D., & Damasio, H. (2001). Emotion recognition from faces and prosody following temporal lobectomy. *Neuropsychology, 15*(3), 396–404.

Altenmüller, E., Schürmann, K., Lim, V. K., & Parlitz, D. (2002). Hits to the left, flops to the right: Different emotions during listening to music are reflected in cortical lateralisation patterns. *Neuropsychologia, 40*(13), 2242–2256. https://doi.org/10.1016/s0028-3932(02)00107-0.

Aubé, W., Angulo-Perkins, A., Peretz, I., Concha, L., & Armony, J. L. (2015). Fear across the senses: Brain responses to music, vocalizations and facial expressions. *Social Cognitive and Affective Neuroscience, 10*(3), 399–407. https://doi.org/10.1093/scan/nsu067.

Belfi, A. M., Evans, E., Heskje, J., Bruss, J., & Tranel, D. (2017). Musical anhedonia after focal brain damage. *Neuropsychologia, 97*, 29–37. https://doi.org/10.1016/j.neuropsychologia.2017.01.030.

Bigand, E., Filipic, S., & Lalitte, P. (2005). The time course of emotional responses to music. *Annals of the New York Academy of Sciences, 1060*, 429–437. https://doi.org/10.1196/annals.1360.036.

Borod, J. C. (1992). Interhemispheric and intrahemispheric control of emotion: A focus on unilateral brain damage. *Journal of Consulting and Clinical Psychology, 60*(3), 339–348. https://doi.org/10.1037/0022-006X.60.3.339.

Borod, J. C., Bloom, R. L., Brickman, A. M., Nakhutina, L., & Curko, E. A. (2002). Emotional processing deficits in individuals with unilateral brain damage. *Applied Neuropsychology, 9*(1), 23–36. https://doi.org/10.1207/S15324826AN0901_4.

Bourgeois–Vionnet, J., Moulin, A., Hermier, M., Pralus, A., & Nighoghossian, N. (2020). A case of verbal and emotional prosody processing dissociation after a right temporal venous infarct. *Neurological Sciences*. https://doi.org/10.1007/s10072-019-04175-w.

Braun, M., Traue, H. C., Frisch, S., Deighton, R. M., & Kessler, H. (2005). Emotion recognition in stroke patients with left and right hemispheric lesion: Results with a new instrument-the FEEL test. *Brain and Cognition, 58*(2), 193–201. https://doi.org/10.1016/j.bandc.2004.11.003.

Charbonneau, S., Scherzer, B. P., Aspirot, D., & Cohen, H. (2003). Perception and production of facial and prosodic emotions by chronic CVA patients. *Neuropsychologia, 41*(5), 605–613. https://doi.org/10.1016/S0028-3932(02)00202-6.

Cheung, C. C. Y., Lee, T. M. C., Yip, J. T. H., King, K. E., & Li, L. S. W. (2006). The differential effects of thalamus and basal ganglia on facial emotion recognition. *Brain and Cognition, 61*(3), 262–268. https://doi.org/10.1016/j.bandc.2006.01.008.

Dellacherie, D., Bigand, E., Molin, P., Baulac, M., & Samson, S. (2011). Multidimensional scaling of emotional responses to music in patients with temporal lobe resection. *Cortex. a Journal Devoted to the Study of the Nervous System and Behavior, 47*(9), 1107–1115. https://doi.org/10.1016/j.cortex.2011.05.007.

Demaree, H. A., Everhart, D. E., Youngstrom, E. A., & Harrison, D. W. (2005). Brain lateralization of emotional processing: Historical roots and a future incorporating "dominance". *Behavioral and Cognitive Neuroscience Reviews, 4*(1), 3–20. https://doi.org/10.1177/1534582305276837.

Egermann, H., Fernando, N., Chuen, L., & McAdams, S. (2014). Music induces universal emotion-related psychophysiological responses: Comparing Canadian listeners to Congolese pygmies. *Frontiers in Psychology, 5*, 1341. https://doi.org/10.3389/fpsyg.2014.01341.

Ekman, P., & Friesen, W. V. (1976). *Pictures of facial affect*. Consulting psychologists Press.

Filipic, S., Tillmann, B., & Bigand, E. (2010). Judging familiarity and emotion from very brief musical excerpts. *Psychonomic Bulletin & Review, 17*(3), 335–341. https://doi.org/10.3758/PBR.17.3.335.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12*(3), 189–198.

Frühholz, S., Trost, W., & Grandjean, D. (2014). The role of the medial temporal limbic system in processing emotions in voice and music. *Progress in Neurobiology, 123*, 1–17. https://doi.org/10.1016/j.pneurobio.2014.09.003.

Gosselin, N., Paquette, S., & Peretz, I. (2015). Sensitivity to musical emotions in congenital amusia. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior, 71*, 171–182. https://doi.org/10.1016/j.cortex.2015.06.022.

Gosselin, N., Peretz, I., Hasboun, D., Baulac, M., & Samson, S. (2011). Impaired recognition of musical emotions and facial expressions following anteromedial temporal lobe excision. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior, 47*(9), 1116–1125. https://doi.org/10.1016/j.cortex.2011.05.012.

Gosselin, N., Peretz, I., Johnsen, E., & Adolphs, R. (2007). Amygdala damage impairs emotion recognition from music. *Neuropsychologia, 45*(2), 236–244. https://doi.org/10.1016/j.neuropsychologia.2006.07.012.

Gosselin, N., Samson, S., Adolphs, R., Noulhiane, M., Roy, M., Hasboun, D., et al. (2006). Emotional responses to unpleasant music correlates with damage to the parahippocampal cortex. *Brain: a Journal of Neurology, 129*(Pt 10), 2585–2592. https://doi.org/10.1093/brain/awl240.

Griffiths, T. D., Warren, J. D., Dean, J. L., & Howard, D. (2004). "When the feeling's gone": A selective loss of musical emotion. *Journal of Neurology, Neurosurgery, and Psychiatry, 75*(2), 344–345. https://doi.org/10.1136/jnnp.2003.015586.

Hamilton, M. (1960). A rating scale for depression. *Journal of Neurology, Neurosurgery, and Psychiatry, 23*, 56–62. https://doi.org/10.1136/jnnp.23.1.56.

Harciarek, M., & Heilman, K. M. (2009). The contribution of anterior and posterior regions of the right hemisphere to the recognition of emotional faces. *Journal of Clinical and*

Experimental Neuropsychology, 31(3), 322–330. https://doi.org/10.1080/13803390802119930.

Harciarek, M., Heilman, K. M., & Jodzio, K. (2006). Defective comprehension of emotional faces and prosody as a result of right hemisphere stroke: Modality versus emotion-type specificity. *Journal of the International Neuropsychological Society: JINS, 12*(6), 774–781. https://doi.org/10.1017/S1355617706061121.

Hartman, D. E. (2009). Wechsler Adult intelligence scale IV (WAIS IV): Return of the gold standard. *Applied Neuropsychology, 16*(1), 85–87. https://doi.org/10.1080/09084280802644466.

Hirel, C., Lévêque, Y., Deiana, G., Richard, N., Cho, T.-H., Mechtouff, L., et al. (2014). Acquired amusia and musical anhedonia. *Revue Neurologique, 170*(8–9), 536–540. https://doi.org/10.1016/j.neurol.2014.03.015.

Jafari, Z., Esmaili, M., Delbari, A., Mehrpour, M., & Mohajerani, M. H. (2017). Post-stroke acquired amusia: A comparison between right- and left-brain hemispheric damages. *Neurorehabilitation, 40*(2), 233–241. https://doi.org/10.3233/NRE-161408.

Joanette, Ska, & Côté. (2004). *Protocole MEC-P - protocole Montréal d'évaluation de la communication de poche*. Cultura.Com. http://www.cultura.com/protocole-mec-p-9782362350030.html.

Johnsen, E. L., Tranel, D., Lutgendorf, S., & Adolphs, R. (2009). A neuroanatomical dissociation for emotion induced by music. *International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology, 72*(1), 24–33. https://doi.org/10.1016/j.ijpsycho.2008.03.011.

Kaplan, E., Goodglass, H., Weintraub, S., & Goodglass, H. (1983). Boston naming test. *Lea & Febiger*.

Khalfa, Delbe, C., Bigand, E., Reynaud, E., Chauvel, P., & Liéégeois-Chauvel, C. (2007). Positive and negative music recognition reveals a specialization of mesio-temporal structures in epileptic patients. *Music Perception: An Interdisciplinary Journal, 25*(4), 295–302. https://doi.org/10.1525/mp.2008.25.4.295.

Khalfa, Guye, M., Peretz, I., Chapon, F., Girard, N., Chauvel, P., et al. (2008). Evidence of lateralized anteromedial temporal structures involvement in musical emotion processing. *Neuropsychologia, 46*(10), 2485–2493. https://doi.org/10.1016/j.neuropsychologia.2008.04.009.

Khalfa, S., Schon, D., Anton, J.-L., & Liégeois-Chauvel, C. (2005). Brain regions involved in the recognition of happiness and sadness in music. *Neuroreport, 16*(18), 1981–1984.

Koelsch, S., Skouras, S., Fritz, T., Herrera, P., Bonhage, C., Küssner, M. B., et al. (2013). The roles of superficial amygdala and auditory cortex in music-evoked fear and joy. *Neuroimage, 81*, 49–60. https://doi.org/10.1016/j.neuroimage.2013.05.008.

Kucharska-Pietura, K., Phillips, M. L., Gernand, W., & David, A. S. (2003). Perception of emotions from faces and voices following unilateral brain damage. *Neuropsychologia, 41*(8), 1082–1090.

Lévêque, Y., Teyssier, P., Bouchet, P., Bigand, E., Caclin, A., & Tillmann, B. (2018). Musical emotions in congenital amusia: Impaired recognition, but preserved emotional intensity. *Neuropsychology*. https://doi.org/10.1037/neu0000461.

Liégeois-Chauvel, C., Bénar, C., Krieg, J., Delbé, C., Chauvel, P., Giusiano, B., et al. (2014). How functional coupling between the auditory cortex and the amygdala induces musical emotion: A single case study. *Cortex; a Journal Devoted To the Study of the Nervous System and Behavior, 60*, 82–93. https://doi.org/10.1016/j.cortex.2014.06.002.

Loonstra, A. S., Tarlow, A. R., & Sellers, A. H. (2001). COWAT metanorms across age, education, and gender. *Applied Neuropsychology, 8*(3), 161–166. https://doi.org/10.1207/S15324826AN0803_5.

Nelson, H. E. (1976). A modified card sorting test sensitive to frontal lobe defects. *Cortex; a Journal Devoted To the Study of the Nervous System and Behavior, 12*(4), 313–324. https://doi.org/10.1016/S0010-9452(76)80035-4.

Niedenthal, P. M. (2007). Embodying emotion. *Science, 316*(5827), 1002–1005. https://doi.org/10.1126/science.1136930.

Nijboer, T. C. W., & Jellema, T. (2012). Unequal impairment in the recognition of positive and negative emotions after right hemisphere lesions: A left hemisphere bias for happy faces. *Journal of Neuropsychology, 6*(1), 79–93. https://doi.org/10.1111/j.1748-6653.2011.02007.x.

Paquette, S., Takerkart, S., Saget, S., Peretz, I., & Belin, P. (2018). Cross-classification of musical and vocal emotions in the auditory cortex. *Annals of the New York academy of sciences*. https://doi.org/10.1111/nyas.13666.

Peretz, I. (1990). Processing of local and global musical information by unilateral brain-damaged patients. *Brain: a Journal of Neurology, 113*(Pt 4), 1185–1205.

Peretz, I., Champod, A. S., & Hyde, K. (2003). Varieties of musical disorders. The montreal Battery of evaluation of amusia. *Annals of the New York Academy of Sciences, 999*, 58–75.

Peretz, I., Gagnon, L., & Bouchard, B. (1998). Music and emotion: Perceptual determinants, immediacy, and isolation after brain damage. *Cognition, 68*(2), 111–141. https://doi.org/10.1016/S0010-0277(98)00043-2.

Pralus, A., Fornoni, L., Bouet, R., Gomot, M., Bhatara, A., Tillmann, B., et al. (2019). *Emotional prosody in congenital amusia: Impaired and spared processes* (p. 107234). Neuropsychologia. https://doi.org/10.1016/j.neuropsychologia.2019.107234.

Sackeim, H. A., Greenberg, M. S., Weiman, A. L., Gur, R. C., Hungerbuhler, J. P., & Geschwind, N. (1982). Hemispheric asymmetry in the expression of positive and negative emotions. Neurologic evidence. *Archives of Neurology, 39*(4), 210–218.

Särkämö, T., Tervaniemi, M., Soinila, S., Autti, T., Silvennoinen, H. M., Laine, M., et al. (2009). Cognitive deficits associated with acquired amusia after stroke: A neuropsychological follow-up study. *Neuropsychologia, 47*(12), 2642–2651. https://doi.org/10.1016/j.neuropsychologia.2009.05.015.

Särkämö, T., Tervaniemi, M., Soinila, S., Autti, T., Silvennoinen, H. M., Laine, M., et al. (2010). Auditory and cognitive deficits associated with acquired amusia after stroke: A magnetoencephalography and neuropsychological follow-up study. *Plos One, 5*(12). https://doi.org/10.1371/journal.pone.0015157.

Satoh, M., Kato, N., Tabei, K.-I., Nakano, C., Abe, M., Fujita, R., et al. (2016). A case of musical anhedonia due to right putaminal hemorrhage: A disconnection syndrome between the auditory cortex and insula. *Neurocase, 22*(6), 518–525. https://doi.org/10.1080/13554794.2016.1264609.

Satoh, M., Nakase, T., Nagata, K., & Tomimoto, H. (2011). Musical anhedonia: Selective loss of emotional experience in listening to music. *Neurocase, 17*(5), 410–417. https://doi.org/10.1080/13554794.2010.532139.

Scherer, K. R. (2004). Which emotions can be induced by music? What are the underlying mechanisms? And how can we measure them? *Journal of New Music Research, 33*(3), 239–251. https://doi.org/10.1080/0929821042000317822.

Stewart, L., von Kriegstein, K., Warren, J. D., & Griffiths, T. D. (2006). Music and the brain: Disorders of musical listening. *Brain: a Journal of Neurology, 129*(Pt 10), 2533–2553. https://doi.org/10.1093/brain/awl171.

Tillmann, B., Albouy, P., & Caclin, A. (2015). Congenital amusias. *Handbook of Clinical Neurology, 129*, 589–605. https://doi.org/10.1016/B978-0-444-62630-1.00033-0.

Tillmann, B., Lalitte, P., Albouy, P., Caclin, A., & Bigand, E. (2016). Discrimination of tonal and atonal music in congenital amusia: The advantage of implicit tasks.

Neuropsychologia, 85, 10–18. https://doi.org/10.1016/j.neuropsychologia.2016.02.027.

Tillmann, B., Schulze, K., & Foxton, J. M. (2009). Congenital amusia: A short-term memory deficit for non-verbal, but not verbal sounds. *Brain and Cognition, 71*(3), 259–264. https://doi.org/10.1016/j.bandc.2009.08.003.

Tippett, D. C., Godin, B. R., Oishi, K., Oishi, K., Davis, C., Gomez, Y., et al. (2018). Impaired recognition of emotional faces after stroke involving right amygdala or insula. *Seminars in Speech and Language, 39*(1), 87–100. https://doi.org/10.1055/s-0037-1608859.

Tsang, C. D., Trainor, L. J., Santesso, D. L., Tasker, S. L., & Schmidt, L. A. (2001). Frontal EEG responses as a function of affective musical features. *Annals of the New York Academy of Sciences, 930*(1), 439–442. https://doi.org/10.1111/j.1749-6632.2001.tb05764.x.

Yuvaraj, R., Murugappan, M., Norlinah, M. I., Sundaraj, K., & Khairiyah, M. (2013). Review of emotion recognition in stroke patients. *Dementia and Geriatric Cognitive Disorders, 36*(3–4), 179–196. https://doi.org/10.1159/000353440.