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Research Report

Functional contributions of the basal ganglia to emotional prosody: Evidence from ERPs

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ABSTRACT

The basal ganglia (BG) have been functionally linked to emotional processing [Pell, M.D., Leonard, C.L., 2003. Processing emotional tone form speech in Parkinson's Disease: a role for the basal ganglia. Cogn. Affec. Behav. Neurosci. 3, 275–288; Pell, M.D., 2006. Cerebral mechanisms for understanding emotional prosody in speech. Brain Lang. 97 (2), 221–234]. However, few studies have tried to specify the precise role of the BG during emotional prosodic processing. Therefore, the current study examined deviance detection in healthy listeners and patients with left focal BG lesions during implicit emotional prosodic processing in an event-related brain potential (ERP)-experiment. In order to compare these ERP responses with explicit judgments of emotional prosody, the same participants were tested in a follow-up recognition task. As previously reported [Kotz, S.A., Paulmann, S., 2007. When emotional prosody and semantics dance cheek to cheek: ERP evidence. Brain Res. 1151, 107–118; Paulmann, S. & Kotz, S.A., 2008. An ERP investigation on the temporal dynamics of emotional prosody and emotional semantics in pseudo- and lexical sentence context. Brain Lang. 105, 59–69], deviance of prosodic expectancy elicits a right lateralized positive ERP component in healthy listeners. Here we report a similar positive ERP correlate in BG-patients and healthy controls. In contrast, BG-patients are significantly impaired in explicit recognition of emotional prosody when compared to healthy controls. The current data serve as first evidence that focal lesions in left BG do not necessarily affect implicit emotional prosodic processing but evaluative emotional prosodic processes as demonstrated in the recognition task. The results suggest that the BG may not play a mandatory role in implicit emotional prosodic processing. Rather, executive processes underlying the recognition task may be dysfunctional during emotional prosodic processing.

1. Introduction

Successful emotional communication is crucial to social interaction. The tone of voice, or emotional prosody, helps to understand how people feel. In particular, listeners must continually monitor and rapidly detect changes in their interlocutor's mood in order to adapt their behavior accordingly during speech perception. Imagine a telephone conversation

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in which your interlocutor is simultaneously reading his credit card bill, and realizes that his wife has spent $1000 on shoes in the past month. It might well be that you are confronted with an abrupt change of tone of voice—from carrying no affect (hereafter referred to as *neutral*) to an *angry* tone of voice. Many other instances in which there are dynamic, and sometimes abrupt deviations in emotional prosody occur regularly in spoken interactions.

We previously showed that participants can very quickly detect changes in emotional prosodic contours, and that such change detection is linked to a right-lateralized positive event-related brain potential (ERP; hereafter referred to as prosodic expectancy positivity, or PEP; Kotz and Paulmann, 2007). Moreover, this deviance detection does not vary as a function of valence (positive vs. negative, Kotz and Paulmann, 2007), or by emotional category (Paulmann and Kotz, 2008). We suggest that the PEP reflects rapid on-line detection of acoustic changes in vocal expressions of emotions independent of attention (implicit and explicit processing), sentence modality (lexical and non-lexical sentence stimuli), and valence (positive and negative). Other positivities elicited by linguistic prosodic deviations, such as the P800 (Astésano et al., 2004) or the closure-positive shift (CPS; Steinhauer et al., 1999) often have a later onset and longer latency than the PEP. For example, the P800 onsets 800 ms post-stimulus (Astésano et al., 2004), while the PEP is elicited approximately 300 ms after the critical position in a sentence. We have proposed that the earlier onset and shorter duration of the PEP may be correlated with the point in time that a stimulus takes on emotional significance (see Paulmann and Kotz, 2008a; Paulmann et al., 2008a).[1] Emotional significance is likely to be conveyed by acoustic parameters, such as pitch, intensity, and more fine-grained parameters, such as voice quality. One major open question is which neural substrates and which underlying mechanism(s) may contribute to this type of significance detection, in particular when prosodic expectancy is violated.

1.1. *Emotional prosodic decoding and neural correlates*

Considerable research has investigated whether emotional prosodic processing relies on hemispheric specialization. Although ample evidence suggests that the right hemisphere (RH) plays a central role in the decoding of emotional prosody (e.g., Breitenstein et al., 1998; Heilman et al., 1984; Pell, 1998), more recent results indicate that emotional prosodic processing involves a bilaterally distributed neural network (Gandour et al., 2004; Kotz et al., 2003; see also Ross et al., 1997; Kotz et al., 2006, for explanations on heterogeneous lateralization results). In fact, there is growing consensus that the RH plays *relative* rather than *absolute* dominance in emotional prosodic processing (see Pell, 2006). While the RH is implicated in the analysis of *emotional* prosodic attributes, the left hemisphere (LH) is often linked to *linguistically*-based processing (e.g., Friederici and Alter, 2004; Pell, 2006; Van Lancker Sidtis et al., 2006). Furthermore, one may argue that the LH serves an integrative function combining verbal-semantic processes with emotion- or pitch-related processes (Pell, 2006; Schirmer and Kotz, 2006).

Next to the issue of lateralization, research has explored the brain network supporting emotional prosodic processing. Evidence suggests that this network is not limited to cortical brain areas, but also involves subcortical areas such as the basal ganglia (BG) (e.g., Cancelliere and Kertesz, 1990; Pell and Leonard, 2003; Pell, 2006; Van Lancker Sidtis et al., 2006). Indeed, the importance of the BG in emotional prosody processing has gained support from patient studies (e.g., Breitenstein et al., 1998, 2001) as well as from functional imaging studies with healthy participants (e.g., Kotz et al., 2003; Wildgruber et al., 2002). It is proposed that the BG play a role in the sequencing of auditory affective information (Pell and Leonard, 2003; Meyer et al., 2004), i.e., it is suggested that BG impairment may cause reduced capability to encode emotionality from affective prosodic cue sequences (e.g., pitch and intensity variations during an emotional utterance; see Pell and Leonard, 2003). Furthermore, it is proposed that this process should interact with cortical associative functions in order to allow evaluating prosodic emotional cues (see Schirmer and Kotz, 2006). It should be critically noted though that neither fMRI nor behavioral patient studies can specify the temporal dynamics of emotional prosodic processing. As behavioral and ERP measures may tap into different processing stages, a combination of a both temporally sensitive measure and behavior should shed more light on process-specific and task-specific effects, and should allow specifying the nature of previously described emotional deficits in BG-patients more precisely. We therefore applied both measures—ERPs and behavior in BG-patients and healthy controls while they listened to emotional prosodic sentences.

1.2. *Aims and rationale*

As reviewed above, some research suggests functionally (emotion vs. linguistic) dependent lateralization of prosodic information processing (Pell, 2006; Schirmer and Kotz, 2006, Pihan et al., 2000). Also, there is some evidence that left- and right-sided lesion patients differ in their use of acoustic cues. For example, right-sided lesion patients are often reported to rely more on temporal cues, while left-sided patients rely more on fundamental frequency (Robin et al., 1990; Van Lancker and Sidtis, 1992). This has led to the hypothesis that the LH is involved in processing temporal cues, while the RH is dominantly engaged in pitch processing. One major motivation of the current study is to find out whether such lateralization principles also apply to patients with subcortical lesions. The detection of abrupt prosodic deviances as described above is clearly based on evaluating pitch change (amongst other acoustical parameters). Hence, to test whether the left BG similarly to left cortical areas do not rely on pitch-related processes, we investigated emotional prosodic change detection in left-sided BG lesion patients in an on-line ERP experiment. Adopting our previously established cross-splicing paradigm (Kotz and Paulmann, 2007; Paulmann and Kotz, 2008), we aimed to replicate PEP responses in healthy participants, and in left-sided BG-patients. Secondly, we asked participants to

[1] In fact, recent evidence comparing the processing of emotional and linguistic prosodic expectancy violation processing confirms an earlier PEP onset in response to deviances to emotional prosody when compared to linguistic prosody deviances (Paulmann et al., 2008a).

recognize the emotional intonation of pseudo-sentences in a follow-up behavioral experiment. If emotional prosodic deviance detection is impaired in BG-patients, this should result in a reduced or missing PEP response. If, however, the online processing of emotionally laden acoustic cues is unimpaired in left BG-patients, healthy controls and BG-patients should show a comparable PEP response. The question remains whether task-related evaluation of emotional prosodic stimuli is affected in BG-patients. If this was the case, we should replicate previously reported emotional prosody recognition deficits as reflected in lower recognition rates for BG-patients than healthy controls in the behavioral follow-up experiment.

2. Results

Behavioral results for the ERP experiment were not analyzed because previous research (Kotz and Paulmann, 2007; Paulmann & Kotz, 2008) has found no effects for prosodic expectancy violations in reaction times or percentage correct responses in healthy participants.

2.1. *ERP results*

ERP mean amplitudes were calculated for violated and non-violated pseudo-sentences in a 2×2×7 analysis of variance (ANOVA) design. *Group* (Healthy controls/BG-patients) was the between-subjects factor, and *M* (prosodically matching, i.e., non-violated, and mismatching, i.e., violated, sentences) and *Scalp Regions of Interest* (*SROI*) were within-subjects factors. Each *SROI* defined a critical region of scalp sites: left frontal: F7 F3 FT7; right frontal: F8 F4 FT8; left central: T7 C3 CP5; right central: T8 C4 CP6; left parietal: P7 P3 O1; right parietal: P4 P8 O2; midline: FZ PZ CZ (see Dien and Santuzzi, 2004 for regional averaging). The null-hypothesis was rejected for *p*-values smaller than .05. The Huynh–Feldt correction (Huyn and Feldt, 1976) was applied to all repeated measures with greater than one degree of freedom in the numerator. Effect sizes were estimated by omega-squared (Olejnik and Algina, 2003), visual inspection, and time-line analyses (see Handy, 2004).

2.1.1.. *850 ms to 1000 ms*

There was no significant difference between the two groups ($F(1,22)=2.17$, $p>.1$; $\omega^2=0.046$). However, the factor M significantly interacted with *SROI* ($F(6,132)=2.76$, $p<.05$; $\omega^2=0.036$). A step-down analysis by *SROI* revealed no significant M effect at left hemispheric electrode sites (all $p>.1$), but a significant *M* effect at right frontal ($F(1,22)=9.85$, $p<.01$; $\omega^2=0.156$), right central $F(1,22)=4.69$, $p<.05$; $\omega^2=0.071$), but not at right posterior electrode-sites $p>.1$). As expected, the ERP waveforms over right frontal and right central electrode-sites were more positive-going for prosodically violated pseudo-sentences than for prosodically non-violated pseudo-sentences shortly after the splicing-point (450 ms).[2]

[2] As our previous evidence showed longer positivities (~100 ms), we also calculated a time window of 850 ms to 1100 ms. While the critical interaction of *M* and *SROI* did not reach significance, we carried out a step-down analysis by *SROI* based on previous evidence. These analyses confirmed a significant positive ERP component for prosodically violated sentences at right frontal and right central electrode sites ($p=.01$), respectively.

2.2. *Emotional prosody recognition results*

Mean percentages correct in the emotional prosody recognition task (irrespective of emotional category) were calculated, and a *t*-test was used to compare means for each participant group (healthy controls vs. BG).

A significant effect of group ($t(22)=3.72$, $p<.01$) confirmed overall higher accuracy scores in emotion recognition in healthy controls than in BG-patients (68.54% vs. 38.75%).

An additional 2×4 ANOVA with GROUP as between-subject factor and emotional category as a within-subjects factor confirmed that the two groups differed in accuracy rates for all emotional categories, but not for specific emotional categories.

3. Discussion

The present study aimed to substantiate why the left BG similarly to left temporal brain regions may not play a significant role in the detection of rapid pitch changes in emotional prosodic contours. Both healthy controls and BG-patients showed a PEP response to emotional prosodic expectancy violations. This replicates our previous results in younger healthy participants (Kotz and Paulmann, 2007; Paulmann and Kotz, 2008) but extends the results to an aging healthy population (mean age: 49 years), and a critical patient population. In contrast, recognition rates obtained in a behavioral emotional recognition paradigm differed significantly between BG-patients and healthy controls, supporting an emotional prosodic recognition impairment in BG-patients. These results nicely complement previous evidence that reported such impairment in BG-patients (e.g., Breitenstein et al., 1998; Starkstein et al., 1994). However, the current results highlight that early and rapid emotional prosodic deviance detection is not impaired in left BG-patients, while off-line recognition of emotional prosodic contours is affected. The implications of such process and task-specific differences will be discussed in the following.

3.1. *BG engagement during early rapid emotional prosodic processing*

One of the main motivations of the present study was to highlight the functional role of the left BG in emotional prosodic processing. The current results suggest that focal lesions in the left BG do not influence early rapid detection of expectancy violations in emotional prosodic contours while off-line recognition of emotional prosody is affected. This suggests that processes such as prosodic change detection (arguably based on frequency-related cues) do not recruit the left BG. However, the off-line recognition results suggest that processes which enforce an integrative evaluation of emotional acoustic information (e.g., evaluation of both frequency-related cues *and* temporal cues as enforced in emotional prosody recognition) or specific task demands (explicit vs. implicit evaluation of emotional prosody) may rely on the left BG. Hence, the question at hand is why left-sided BG-patients show impaired emotional prosody recognition in pseudo-sentences while rapid prosodic deviance detection in emotional context is still intact.

A previously proposed model of emotional prosodic processing by Schirmer and Kotz (2006) allows addressing this issue. The model assumes three broadly defined processing stages. Following sensory processing (stage 1), emotionally significant acoustic cues are integrated to form an emotional "Gestalt" (stage 2). Lastly, evaluation of emotional stimuli takes place (stage 3). The authors suggest that top–down mechanisms triggered by attention, and bottom–up mechanisms activated by emotional significance can impact all processing stages. Most importantly, bottom–up mechanisms may be mediated by subcortical structures such as the amygdala (e.g., LeDoux, 2002) and alter emotional behavior (Schirmer and Kotz, 2006). Whether bottom–up/top–down differentiation is also channeled by the BG remains a matter of debate. Following the proposed model the current data suggest that the left BG are not critically involved in early processing stages (i.e., integration of emotionally significant acoustic cues), a processing stage enforced by prosodic expectancy violations.[3] However, the left BG may be of primary importance during the following stages when evaluation of emotional prosody takes place (i.e., during recognition). Alternatively, the current data may suggest that the basic capacity to register prosodic deviance can be influenced by bottom–up processes mediated by the BG that in turn alter emotional behavior. In fact, some authors have previously argued that the BG are an excellent candidate in evaluating and supporting incoming sensory information, assisting a contextually proper behavioral response (see Pell and Leonard, 2003). As the PEP is comparable between BG patients and healthy controls, one can argue that incoming sensory information (processes reflected in the PEP) is not used appropriately to carry out behavioral responses. Hence the observed impairment in the emotional prosody recognition task in left BG patients. Clearly, this interpretation is speculative and needs to be directly tested in further studies with right BG patients.

3.2. *The BG and lateralization of emotional prosodic processing*

Moreover, Schirmer and Kotz (2006) proposed that the integration of emotionally significant acoustic cues is a dominantly right–lateralized cortical process. Specifically, we previously stated that the LH serves an integrative and interpretative function combining verbal-semantic processes with emotion- or pitch-related processes (Pell, 2006; Schirmer and Kotz, 2006). The present data support this hypothesis as left BG-patients seem to register acoustic cues in emotional prosodic deviances (hence the intact PEP response); however, the behavioral impairment reported here may be caused by deficient integrative processes that recruit LH brain regions. In fact, support for this hypothesis comes from the same patients, who suffer from an impairment processing emotional prosodic *and* semantic expectancy violations (Paulmann et al., 2006). Processing of combined expectancy violations seems to rely on the LH more strongly (due to additional semantic information processing) than pure (emotional) prosodic deviance processing. Along similar lines, Pihan and colleagues (2000) report RH involvement during emotional prosodic processing in DC potential studies with additional LH activation when participants used inner speech. The authors argued that inner speech leads to "a differential weighting of acoustic parameters used for evaluation of emotional content: A relative increase of LH activation mediated by temporal cues and a reduced RH processing of frequency-related information" (Pihan, 2006). This evidence is in line with previous studies that put emphasis on the difference between LH patients and RH patients with regard to the use of acoustic stimulus properties in (emotional) prosodic processing (Van Lancker and Sidtis, 1992; Robin et al., 1990). Thus, we assume that emotional prosodic deviance detection is more strongly based on frequency-related deviances than on temporal cue deviance.

Finally, the right-lateralized PEP component elicited in emotionally intoned pseudo-sentences substantiates previous evidence suggesting lateralization of emotional prosody (e.g., Vingerhoets et al., 2003). On a critical note though, it has been shown that task demands may influence lateralization effects (Kotz and Paulmann, 2007; Kotz et al., 2006; Pihan et al., 2000). Lesions to the left BG may not affect emotional prosodic deviance detection as reflected in the PEP component despite possible bilateral BG involvement during early rapid emotional prosodic processing dependent on task and function (see e.g., Paulmann et al., 2006, for a modified early ERP component, P200, in the same patient group). Taken together, we propose that the current results add to the evidence that the processing of emotional acoustic cues (i.e., pitch) is functionally right-lateralized in cortical and subcortical structures. This in turn explains why the current patient population is unaffected during early stages of emotional prosodic processing, but does suffer from emotional prosody recognition deficits at a later stage in processing.

3.3. *The BG and emotional prosodic processing under attentional/executive control*

The current results also highlight the importance of distinguishing between early rapid and later attentional emotional prosodic processing stages. We tried to specify the contribution of the BG during emotional prosodic processing, and were able to show that the left BG are not involved in all stages of emotional prosody processing. In particular, we were able to show that BG involvement is linked to task-specific effects during emotional prosodic processing, as reflected in the dissociation of early ERP effects and later behavioral responses. The present behavioral control study qualifies only in a limited way to discuss emotional prosody recognition processes due to the low, albeit highly valid, number of pseudo-sentences that had to be recognized. Nevertheless, results emphasize that processes related to the evaluation and output behavior of emotional stimuli is affected in BG-patients, an outcome in line with previous studies (e.g., Blonder et al., 1989; Breitenstein et al., 1998, 2001; Pell, 1996; Pell and Leonard, 2003).

Unfortunately, the present design does not allow differentiating implicit and explicit emotional prosodic processing

[3] Interestingly, the latency of the current positivity is delayed by 100 ms in comparison to previous studies (Kotz and Paulmann, 2007; Paulmann and Kotz, 2008). However, as previous research has shown that age of participant can influence emotional prosodic processing (e.g., Paulmann et al., 2008a,b), we argue that the later onset could be due to the advanced age of participants tested in the current study.

mechanisms as engaged in each experimental part of the current study. While behavioral output always requires explicit emotional prosodic processing, we chose to test emotional prosody implicitly in the ERP part in order to ensure more natural-like language processing. Though we cannot exclude the possibility that the current differentiation between early rapid and later attentional processing mechanisms are in part confounded with task effects, previous evidence suggests that implicit and explicit processing of expectancy violations elicit a similar PEP response in healthy participants (Kotz and Paulmann, 2007), making it less likely that the effects presented here are solely task-related.

3.4. *Conclusion*

The present study allowed comparing the effects of different emotional prosodic processing stages in left BG patients and healthy controls. Results clearly delineate the importance to differentiate between different emotional prosodic processing stages. In fact, results revealed unimpaired early emotional prosodic deviance detection in left BG patients, while a late emotional prosody recognition impairment was observed in the same patients. Moreover, the current ERP investigation allowed separating process-correlated task effects as reflected in behavioral responses from a potential on-line emotional processing deficit. In summary, results suggest that the left BG may not play a mandatory role in on-line emotional prosodic processing, but that executive processes underlying the recognition task may be dysfunctional during emotional prosodic processing. Clearly, given the reported dissociation between implicit and explicit emotional prosodic processing, future studies should carefully consider such task manipulations. Finally, most previous studies have engaged patients with degenerative disorders, such as Parkinson's and Huntington's disease. Here, patients with focal lesions of the BG were tested to ensure that previously reported emotional deficits in patients are not only related to the pathology associated with degenerative diseases.

4. Experimental procedures

4.1. *Participants*

Twelve chronic patients (1 female, all right-handed; mean age: 49.2 years) with focal lesions in the striatum participated in the study after giving informed consent. Lesions resulted from LH insults: ischemic stroke ($n=3$), embolic stroke ($n=3$), hemorrhage ($n=3$), intracerebral bleeding (ICB; $n=3$), or arterio-arterial infarction ($n=1$). The average time post-lesion was: 4.6 years (range 1.8–7.1). Lesion sites were determined by (T1- and T2-weighted) anatomical MRI datasets from a 3.0 T system (Bruker 30/100 Medspec) and evaluated by an experienced neuroanatomist. All patients were non-aphasic and showed no noticeable results on standard neuropsychological testing (e.g., Behavioral Assessment of the Dysexecutive Syndrome [BADS], Wechsler Gedächtnistest [WMR-S]). Individual patient information can be found in Table 1. In addition, twelve healthy controls were tested. All participants were native speakers of German. The groups were age-, education-, and gender-matched. See Fig. 1 for a graphical display of a lesion overlay and Table 1 for demographic patient information.

4.2. *Stimulus material*

The base stimulus material consisted of language-like pseudo-sentences (e.g., "Hung set den Nestol verbarsicht ind gekobelt"), that is, sentences with no lexical-semantic content but clearly conveying one of three negative emotions (*angry*, *disgust*, *fear*) or *neutral* affect. Sentences were spoken by a trained male speaker, and were taped with a video camcorder (SONY Digital Video camera Recorder MiniDV DCR-TRV60E) attached to a high-

Table 1 – Demographic patient information

Patient	Sex	Age at test (years)	Time since lesion (years)	Etiology	Lesion description
01	M	63	7.04	Hemorrhage	Ant. GPe, ant. IC
02	M	53	6.01	ICB	Post. Put., GPe, post. EC, IC, lat. Thal.
03	M	48	5.01	ICB	Put., GPe, EC, ant. IC, reduced volume of Caud.
04	M	31	5.05	Ischemic infarct	Post. Put., Caud. (body), middle Ins., parietal operculum
05	M	68	4.04	Ischemic infarct	Caud. (ant. body), ant. Put., GPe, EC, ant. IC, ant. Ins., preinsular WM
06	F	40	3.03	Arterio-arterial infarct	Caud. (body), Put., GPe, ant. IC, EC, parietal operculum, post. Ins.
07	M	59	4.11	Ischemic infarct	Caud. (body), Put., GPe, IC, EC
08	M	66	7.11	Hemorrhage	Caud., Put.
09	M	33	6.00	Embolic infarct	Put., Caud.
10	M	28	1.08	Hemorrhage	Post. Put., Caud.
11	M	26	3.05	ICB	Thal., post. Put., Caud.
12	M	75	4.11	Embolic infarct	Caud. (body), Put.,

The table shows demographic patient information. Lesions resulted from LH insults: ischemic stroke ($n=3$), embolic stroke ($n=3$), hemorrhage, ($n=3$), intracerebral bleeding (ICB; $n=3$), or arterio-arterial infarction($n=1$). The average time since lesion in the basal ganglia was: 4.6 years (range 1.8–7.11). Lesion sites were determined by (T1- and T2-weighted) anatomical MRI datasets from a 3.0 T system (Bruker 30/100 Medspec) and evaluated by an experienced neuroanatomist. Note: m = male, f = female, ICB = intracerebral bleeding, ant. = anterior, post. = posterior, Caud. = caudate nucleus, EC = external capsule system, IC = internal capsule, Ins. = insula, GPe = globus pallidus externus, GPi = globus pallidus internus, Put. = Putamen, Thal. = thalamus, WM = white matter.

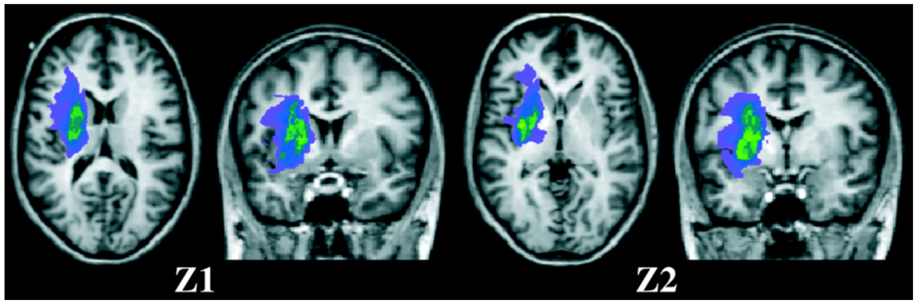

Fig. 1 – The illustration shows an overlay of respective individual patient lesions indicating maximum overlap in the basal ganglia. Displayed are two slice levels (Z1=89[originally 1–180]; Z2=102[originally 1–180]). Green/yellowish shades reveal maximum overlap of lesion sites, whereas purple shades reveal minimal lesion site overlap.

quality clip-on microphone. The video-material was digitized, and the voice-track was separated from the visual-track. In the current experiment, only voice material was tested. The voice material was digitized at a 16-bit/44.1 kHz sampling rate, and the amplitudes were individually normalized (with *CoolEdit* Version 2000). Results from acoustical analyses can be found in Table 2.

4.2.1. *ERP experiment*

In the ERP experiment, 120 language-like pseudo-sentences conveying one of three negative emotions (*angry*, *disgust*, *fear;* 30 sentences each) or *neutral* affect were presented. In addition, the same sentences were presented in a cross-spliced condition. To this aim, a *neutral* first half of a pseudo-sentence ("Mon set"/ "Hung set") was cross-spliced to a prosodically emotional (*angry*, *disgust*, *fear*) second half of a pseudo-sentence. This procedure resulted in 90 prosodically-violated pseudo-sentences (see Fig. 2 for a graphical illustration of splicing-procedure; and see Kotz and Paulmann, 2007, for a more detailed explanation on the procedure). The splicing-point was determined by calculating the mean duration of the neutral start of the pseudo-sentences that were used as a splicing template (here "Mon set"/"Hung set"). The mean splicing point occurred approximately 400 ms after sentence onset. A total of 540 trials (not all results reported here) were presented in one session.

4.2.2. *Behavioral recognition experiment*

A classical forced-choice emotional prosody recognition study followed the ERP study. Here, a total of 100 trials were presented (again, not all results reported here). For the recognition experiment only non-violated, prosodically matching sentences (10 from each emotional category and neutral) were used. The emotional category for non-violated pseudo-sentences was obtained in an earlier rating study. In this study, 24 participants (12 female) rated the pseudo-sentences according to their emotion (forced-choice task) and in a second step, they rated the intensity of that same stimulus on a 5-point scale that ranged from −2 to +2 for emotional intensity. The sentences presented were the top-10 from the previous rating study, hence, ensuring very good quality of emotional prosody portrayal (with mean recognition rate obtained from healthy participants ranging above 80% correct for pseudo-sentences).

Table 2 – The table shows results of acoustic analyses from prosodically deviant and non-deviant stimuli (measured from sentence onset to sentence offset)

Condition	Mean F0	SD	Mean dB	SD	Mean dur	SD
Anger	252.33	16.76	71.52	1.91	2.92	0.27
Disgust	215.49	30.19	68.70	2.59	3.62	0.31
Fear	194.21	50.03	67.87	3.09	4.05	0.70
Anger deviance	242.15	15.63	71.62	1.74	2.97	0.30
Disgust deviance	209.93	28.34	68.63	2.21	3.52	0.30
Fear deviance	185.08	38.28	68.37	2.58	3.75	0.55

4.3. *Procedure*

4.3.1. *ERP experiment*

Participants were seated in a comfortable chair at a distance of 115 cm from a computer monitor. Each participant was tested individually in a sound-attenuating room with a two-button panel placed before him/her. Half of the participants pressed the yes-button with their right hand and the no-button with their left hand, whereas the other half of the participants responded in the opposite manner. The sentences were presented via loudspeaker at a comfortable listening level. Participants were directed to listen to each sentence, to read a word which followed the sentence, and to make a decision as quickly as possible whether the word had been previously heard in the spoken sentence. Participants had to respond within 8000 ms. The inter-trial interval was 1500 ms. Before the actual experiment, a practice session with 20 trials was carried out.

4.3.2. *Behavioral recognition experiment*

The behavioral emotional prosody recognition study was carried out after the ERP experiment in the same sound-attenuating room. All participants had at least 25 min time

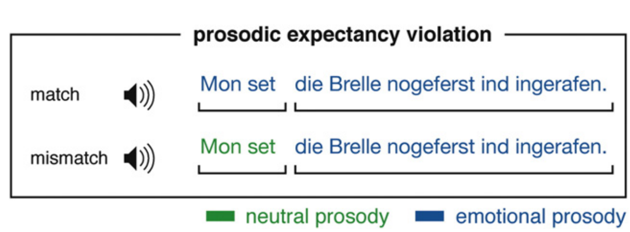

Fig. 2 – The illustration explains the splicing procedure.

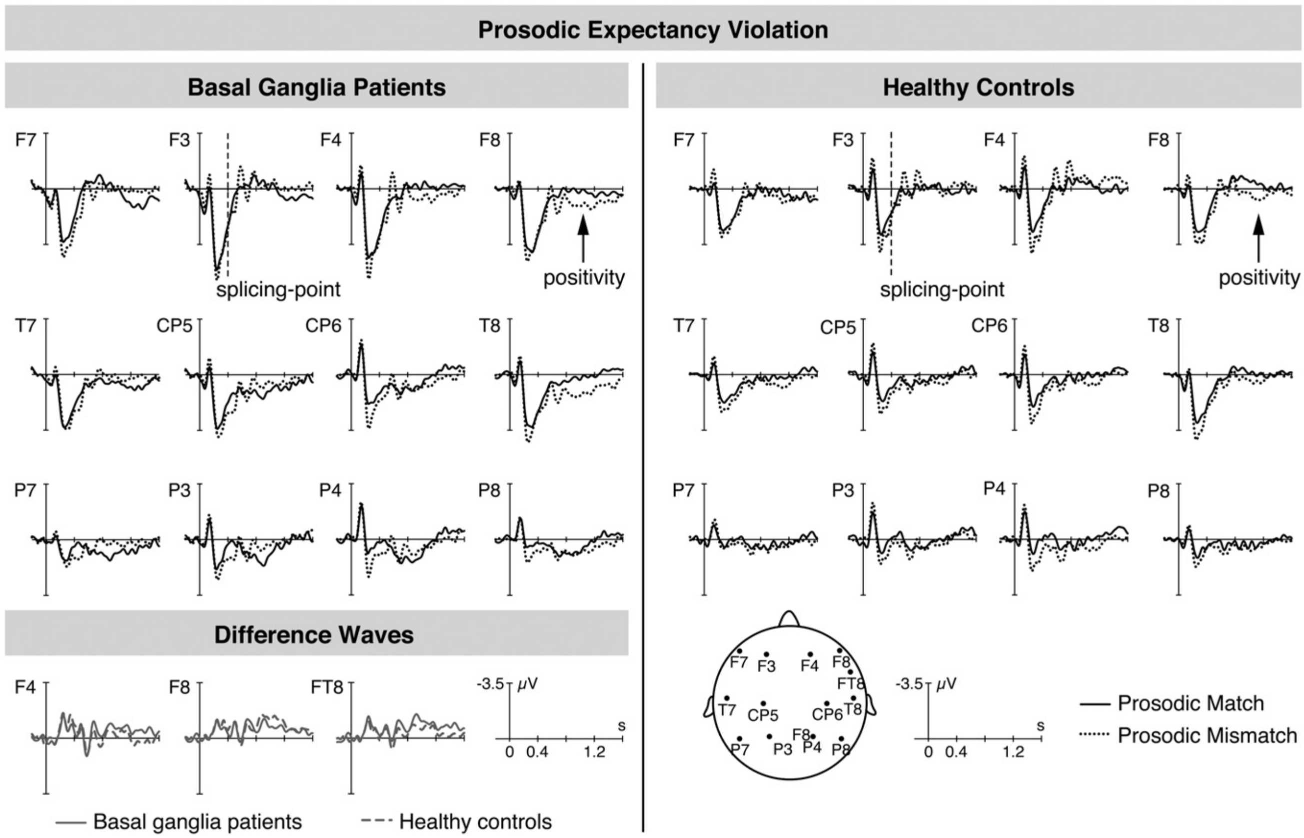

Fig. 3 – The illustration displays the ERP-effects elicited by emotional prosodic expectancy violations averaged across all trials and participants of each group. Waveforms show the average for prosodically unviolated (prosodic match, solid line) and prosodically violated (prosodic mismatch, dotted line) sentences from 100 ms before stimulus onset up to 1600 ms poststimulus onset. Both groups show the expected prosodic expectancy positivity (PEP).

between the ERP experiment and the behavioral study. Again, each participant was tested individually, and was seated comfortably with a button response box before him/her. Each response button on the response panel was labeled with a name of one of the emotional categories tested. Sentences were presented via loudspeaker. Directions, with examples, asked participants to listen to the presented sentence and to make a decision as accurately as possible, which emotional category the emotional prosody of the presented sentences corresponded to. Answers had to be given within 8000 ms. The inter-trial interval was again set at 1500 ms. A practice session preceded the experiment.

4.4. *ERP recording*

The electroencephalogram (EEG) was recorded from 32 Ag–AgCl electrodes mounted on a custom-made cap (Electro-Cap International) according to the modified expanded 10–20 system (Nomenclature of the American Electroencephalographic Society, 1991). Signals were recorded continuously with a band pass between DC and 70 Hz and digitized at a sampling rate of 250 Hz. Electrode resistance was kept below 5 K-Ω. The reference electrode was the tip of the nose. Data were re-referenced offline to linked mastoids. Eye artifact control measures were applied to the raw data of each participant to increase the number of critical trials in each condition (Pfeifer et al., 1995). Subsequently, individual EEG recordings were scanned for additional artifacts on the basis of visual inspection. ERPs were filtered off-line with a digital FIR bandpass filter ranging from 0.298 to 30 Hz (−6 dB cutoff; 1471 points). ERPs were averaged for epochs of 1600 ms starting 200 ms before sentence onset thus including a 200 ms pre-stimulus baseline. Data quantification was constrained by a time-line analysis of the whole epoch. Based on these systematic statistical tests and close visual inspection time windows were defined for further ERP analyses of mean amplitudes. For graphical display only, ERPs were filtered off-line with a 7 Hz low pass filter (Fig. 3).

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