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Hits to the left, flops to the right: different emotions during listening to music are reflected in cortical lateralisation patterns

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Abstract

In order to investigate the neurobiological mechanisms accompanying emotional valence judgements during listening to complex auditory stimuli, cortical direct current (dc)-electroencephalography (EEG) activation patterns were recorded from 16 right-handed students. Students listened to 160 short sequences taken from the repertoires of jazz, rock-pop, classical music and environmental sounds (each $n = 40$). Emotional valence of the perceived stimuli were rated on a 5-step scale after each sequence. Brain activation patterns during listening revealed widespread bilateral fronto-temporal activation, but a highly significant lateralisation effect: positive emotional attributions were accompanied by an increase in left temporal activation, negative by a more bilateral pattern with preponderance of the right fronto-temporal cortex. Female participants demonstrated greater valence-related differences than males. No differences related to the four stimulus categories could be detected, suggesting that the actual auditory brain activation patterns were more determined by their affective emotional valence than by differences in acoustical "fine" structure. The results are consistent with a model of hemispheric specialisation concerning perceived positive or negative emotions proposed by Heilman [Journal of Neuropsychiatry and Clinical Neuroscience 9 (1997) 439].

Keywords: Emotions; Music; Environmental sounds; Brain activation patterns; Hemispheric lateralisation; dc-EEG

1. Introduction

Music and sound processing rely on widely distributed cortical neural networks involving superior temporal and dorsolateral frontal lobes, and also parietal brain regions [36,39,43,44]. Listening to music however is much more than processing acoustic patterns; music can be a powerful tool to elicit emotions.

Little is known about the neurobiological basis of these emotions. Three case reports describe a dissociated impairment of the emotional musical qualities following right temporal lesions. In two cases, this impairment was bound to deficits in timbre perception [27,33]. The remaining case presented with a larger temporo-parietal lesion. This patient suffered in addition to the loss of aesthetic enjoyment of music of impaired melodic, timbre and pitch perception [32].

Another very thoroughly studied case demonstrated a dissociated loss of non-emotional judgement but relative preservation of emotional judgement of music following extended lesions which included on the left side the anterior part of the left temporal lobe, the posterior aspect of the frontal operculum, the anterior parahippocampal gyrus, and parts of the inferior parietal lobule. On the right side, the reported patient had lesions of the inferior and middle frontal gyrus, the precentral gyrus, and of the insula with extension into the lateral orbito-frontal gyri and putamen [37]. Although—due to the multiplicity of lesions—it is difficult to draw conclusion concerning the exact distribution of neuronal networks involved in processing of emotions from such a case, there remains a dissociation of "intellectual" music perception and "emotional" music processing, which may occur in both directions following brain damage. Systematic lesion studies concerning these types of defective perception have yet to be performed.

From lesion studies it is clear that the cerebral cortex and in particular the frontal lobes play an important role in many aspects of human emotional behaviour and experience [28]. Different hypotheses have been advocated to describe the specific roles both hemispheres play in asymmetric control of affect. The first hypothesis dates back to Jackson [24], who observed that damage to the left hemisphere was more likely to cause severe depression and "catastrophic reactions" whereas damage to the right hemisphere produced inadequate indifference or even euphoria in some patients.

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It was concluded that emotional behaviour is organised in a "balanced" manner, with a unilateral lesion producing a relative preponderance of the emotions processed in the contralateral hemisphere. As a consequence, it was postulated that positive emotions are primarily processed in the left, negative emotions in the right hemisphere [19]. Recently, Heilman [22] elaborated this theory and discussed a model of a modular cortical network, regulating the activities of the limbic system and mediating subjective emotional experience. According to this model, the frontal lobes are important for valence, with the left mediating positive emotions, the right negative emotions. Furthermore, the right hemisphere is important in activating arousal systems, and the left modulates inhibition of these systems. Finally, according to this theory, the orbito-frontal regions mediate avoidance behaviours, and the parietal lobes mediate approach behaviours. All these cortical regions are closely interconnected with the limbic system, the basal ganglia and reticular systems.

In healthy participants, two dichotic listening studies have investigated brain lateralisation during emotional music processing. Bryden et al. [12] demonstrated a left ear advantage for identifying the emotional quality of musical stimuli. Gagnon and Peretz [18] distinguished between affective and non-affective processing of the same musical stimuli. They presented monaural melodies that either conformed to the rules of the western tonal system or that systematically deviated from it. One group of participants had to judge whether each melody sounded correct or not—the "non-affective" task, the other group judged whether the melodies sounded pleasant or not—the "affective" task. While there was no ear difference detectable in the non-affective task, there was a clear ear difference in the affective task. This depended on the emotional valence of the response. Pleasant melodies were accompanied by a right ear advantage, unpleasant melodies by a left ear advantage, supporting the idea that the left hemisphere is biased towards positive, right hemisphere towards negative emotions.

Emotional responses to music have been studied utilising positron emission topography (PET) [9], differences in brain activation were assessed when normal volunteers listened to novel melodies sounding more or less consonant or dissonant by varying the harmonic structure of its accompanying chords. Participants rated the most dissonant melodies most unpleasant and vice versa, the most consonant melodies most pleasant. Subtractive PET revealed an increase of cerebral blood flow in the right parahippocampal gyrus with increasing level of dissonance and a decrease of blood flow in the orbito-frontal cortex and the subcallosal cingulum. All three regions are part of the limbic "emotion-processing" system [31,41]. No differences in neo-cortical activation of the two hemispheres related to the sensed pleasantness or unpleasantness were detected.

Utilising electroencephalography (EEG—alpha power rather than direct current (dc)-potentials), emotions of four orchestral pieces were rated on valence and intensity [42]. The authors found a greater relative to the left frontal EEG in positive stimuli and greater relative to the right frontal activity for negative stimuli. The authors included intensity to investigate Heller's [23] model of emotion, which proposes a frontal and right parieto-temporal involvement in emotion. Furthermore, the right parietal region is thought to be associated with higher levels of arousal. The authors showed that the pattern of EEG asymmetry was not distinguished by intensity of emotions.

Emotional valence attributions during listening to music depend in part on gender [13]. In Germany, female adolescents attribute to a greater extent positive valence to "soft music" compared to males. On the other hand, male adolescents seem to attribute positive valence to more aggressive hard-rock and heavy metal music [10]. Whether this is due to gender-specific cultures of musical taste or to more general gender differences in processing of music is open.

Gender differences in processing of emotions have been demonstrated. Davidson et al. [16] found greater right hemisphere activation during self-induced affective states in females compared to males with EEG. More recently, gender differences in subcortical neural circuits were shown using fMRI whilst viewing photographs of faces expressing fear. The authors found that during adolescent development, only females showed a progressive increase in left prefrontal regions relative to amygdala. In contrast, males failed to show significant age-related differences [25].

The present study was designed to clarify the neurobiological background of valence judgements related to emotional processing of complex auditory stimuli. In order to cover a broader range of auditory stimuli, environmental sounds were also included with pieces of different musical styles. The rationale behind this approach was to examine whether brain networks related to emotional valence judgements are influenced by the character of the stimuli (different music styles and environmental sounds) or by the emotional response. Valence judgements were utilised to provide an objective measure of a relatively subjective experience. Furthermore, a group of relatively young participants were chosen to ensure that the participant's rating was more related to actual emotions felt rather than 'concepts' about different musical styles. According to Behne [6,7], youths of age between 12 and 15 years are particularly open minded when confronted with new auditory experiences.

2. Methods

2.1. Measurement

To assess brain activity, a non-invasive EEG technique was applied. Afferent input to the cerebral cortex—i.e. cortical "activation"—causes an increase in negative field potential at the apical dendrites of cortical pyramidal cells. The local distributions of low frequency, negative dc-potentials, reflect cortical activation patterns. Since these dc-potentials have lower voltage than the ongoing background EEG, the signal-to-noise ratio has to be enhanced by averaging task-related EEG activity over 20–40 trials. It is therefore necessary to present a larger number of different stimuli to gain reliable results. Activation patterns obtained by this method are highly task-specific and intra-individually reproducible (for neurophysiological details of the method, see [3,4]).

2.2. Participants and general procedure

Sixteen right-handed students (eight female, eight male), aged 12–15 years with similar musical and general educational background participated in the experiment. All attended to the seventh, eighth or ninth grade of two "classical" grammar schools in Hanover. This type of school focuses on classical languages and is rated as a demanding education in Germany. Students start in the fifth grade with Latin as first foreign language, in the seventh grade with English and in the ninth grade with either ancient Greek or French. All participants came from upper middle class academic households; their parents were mainly employed as doctors, engineers, teachers or state employees. All participants played at least one instrument for at least 3 years (range 3–9 years) and received additional instruction with private teachers or in a public music school of Hanover. With their instruments (eight piano, five strings, three woodwinds) they were enrolled in traditional teaching programs focussing on technical exercises and classical literature.

Handedness was assessed using the Edinburgh inventory [35]. All participants gave informed consent to the proceedings during the experiment, which were approved by the local ethics committee.

Participants listened to 120 short pieces of music and to 40 environmental sounds, which were all 15 s long. During listening, dc-EEG-brain activation patterns were assessed with 32 electrodes over both hemispheres. After each stimulus presentation, participants were asked to rate their emotional valence. They had to rate on a 5-point scale, whether they liked or disliked the music or sounds presented (1: like very much, 2: like, 3: undecided, 4: do not like, 5: do not like at all). Ratings of "I like very much", or "I like" were considered as a positive valence judgement. In contrast, stimuli evaluated with "I do not like" or "I do not like at all" were regarded as negative valence judgements. Participants were encouraged "not to think too much about it" and to rely mainly on their "feelings".

2.3. Stimuli

Since the aim of the study was to relate valence judgements to the brain activation patterns, a broad variety of 160 stimuli were selected. A list of all stimuli used in the experiment is given in Appendix A.

Stimuli were selected from four categories of music and sounds, respectively: (1) jazz, (2) rock-pop, (3) classical music, and (4) environmental sounds ($n = 40$ each). During the experiment, stimuli were presented in a random order. Vocal music was not included in the set to avoid language-related brain activation. Furthermore, to minimise recognition effects, only less popular pieces of music were selected (see Appendix A). Classical music was selected from rarely played repertoire in Germany, pop, rock, and jazz music from recordings mostly older than 10 years. After the experiment, participants were informally asked whether they had recognised the music. They responded having recognised in-between 0 and 10 stimuli from hearing, but were unable to name composer, groups, etc. Environmental sounds were taken from natural sounds and industrial domains. Although they could be more easily recognised in their overall character (e.g. birds chants during rain, walking noises in the snow, chain saw, etc.) the details of the auditory scenery were difficult to identify.

There were two pilot studies investigating the emotional (positive/negative) aspects of the stimuli. Firstly, in order to cover a wide range of emotional responses stimuli were chosen from a large variety of heterogeneous styles. Stimuli were selected so that a half of the stimuli should produce a more negative response and the other half a more positive response. Furthermore, considerable care was taken for the classification of negative and positive stimuli. They were balanced concerning the level of arousal they produce. Fast movements for example were regarded to be more "activating" compared to slow movements. Therefore, the same number of fast and slow pieces of music in the positive and negative category was matched. To evaluate the valence judgement in advance, in a pilot experiment, 40 items from classical and popular music were tested in a group of students not participating in the EEG experiment. In general, more dissonant sounding music produced negative valence judgements with higher probabilities. Furthermore, pop music produced positive valence judgements with higher probabilities compared to jazz and classical music.

The second pilot study involved members of the staff of the institution to rate and select out of a body of more than 200 stimuli the remaining 120 stimuli with respect to either negative or positive feelings while listening. Consistent with previous research into the habits and attitudes of music consumption in young students in Germany, negative emotions were elicited by more dissonant sounding pieces of music, such as extracts from compositions of Pierre Boulez (e.g. "Le marteau sans maitre"), whereas positive emotions were attributed to compositions in the "softer" pop-style, but equally in baroque and classical style such as for example piano pieces of Scarlatti [6,7].

Stimuli were prepared by using high quality CD recordings. In a first step, the music was digitised, each piece was 15 s in duration. The short sequences were complete musical phrases. Subsequently, the sound pressure level of each stimulus was adjusted to a mean of approximately 66 dBA.

In order to avoid startling the participants, the beginning and the end of each stimulus were faded in and out, respectively.

2.4. Recording procedures

Participants were seated comfortably at a distance of 2 m in front of high quality stereo loudspeakers. They listened to the sequences and were asked to tell the experimenters about their "valence" judgement right after the end of each stimulus. While listening, the dc-EEG was recorded from 32 electrodes positioned according to the international 10/20 system over frontal, central, temporal, and parietal brain areas of both hemispheres using the standardised Electro-Cap device (Electro-Cap International, Eaton, OH). A linked-earlobe electrode served as a reference. Impedance was maintained below 3 kΩ. Bipolar electrode montages recorded eye movements, which were later used for artefact rejection. To record the very low dc-frequencies of the EEG, a commercially available dc-amplifier system (Neuroscan/USA) was used. The frequency band of amplification ranged from dc to 30 Hz. The amplified signals were digitised at a 100 Hz sample rate and analysed off-line.

2.5. Data analysis for brain activation

Trials contaminated with artefacts were excluded from further analysis. For data quantification, mean amplitudes of brain activation during the 14 s of the stimulus presentation period were calculated for each trial and related to a baseline taken from a 1 s pre-stimulus interval. The 15th second was disregarded because of interference with artefacts caused by the preparation of the verbal utterance of the valence judgement. Independent variables were "valence categorisation" (two levels: positive versus negative), "stimulus" (classic, jazz, rock-pop, environmental sounds), "gender" (female versus male), "electrodes" (32 levels, according to all electrode positions) and "laterality", i.e. the difference of activity in homologous pairs of electrodes on either hemisphere (10 levels, according to the number of paired electrodes). Amplitude values at 32-electrode positions were considered as dependent variables and ANOVA was performed. In order to evaluate the changes in topographical distributions rather than amplitudes, all values were normalised according to the criteria formulated by McCarthy and Wood [34] and ANOVA were repeated on this normalised values. As a rather conservative approach, results were regarded as significant, when statistics performed on amplitude values and on the normalised data set both yielded significant results. The behavioural measures were analysed using repeated measures ANOVA and for simple effects analysis all paired comparisons were corrected with the Bonferroni adjustments.

3. Results

3.1. Behavioural data

The emotional valence judgements of the male and female participants are depicted in Fig. 1. This figure shows that there was a significant interaction between valence ratings and musical category ($P < 0.01$). Simple effects analysis

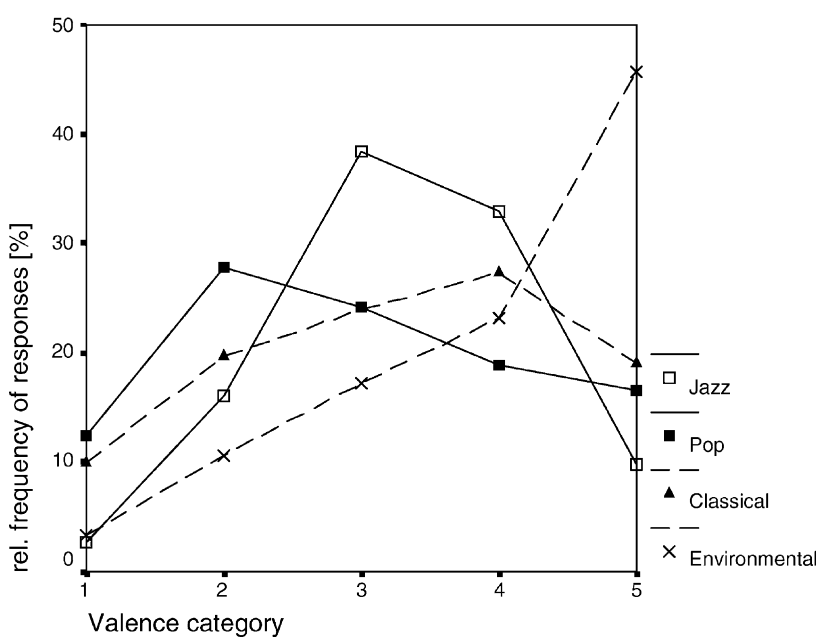


Fig. 1. Emotional valence ratings for the four groups of stimuli (jazz, pop, classical music and environmental sounds). Valence ratings were completed on a 5-step scale: 1, like very much; 2, like; 3, undecided; 4, do not like; 5, do not like at all. Pop music presented more positive attribution, valence ratings for jazz music follows a relatively normal distribution, while classical music has greater negative attribution and finally environmental sounds display a function with an increasing dislike.

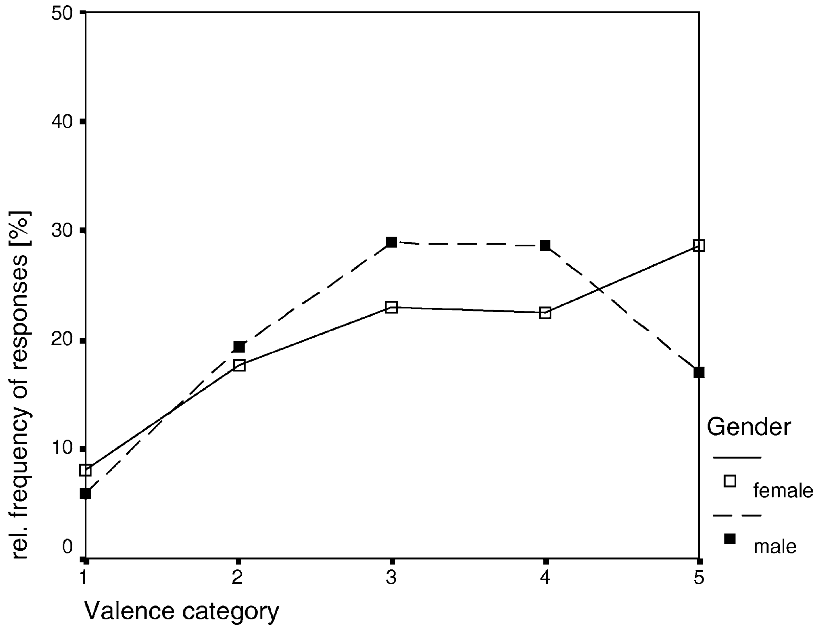


Fig. 2. Mean frequencies of the respective valence attributions in percent according to different styles for males and female participants. All types of stimuli (each $n = 40$ per subject) are included. Ratings were done on a 5-step scale: 1, like very much; 2, like; 3, undecided; 4, do not like; 5, do not like at all.

was performed to investigate the significant interaction further. Significant differences for each valence between musical categories are as follows: For valence rating 1 ("like very much"), the percentage of responses in the jazz category was less than pop music (10%); pop music was more liked than environmental sounds (9%). Pop music was also liked more in valence rating 2 ("like") than environmental sounds (17%). For valence rating 3 ("undecided"), jazz was significantly more undecided than pop (14%), classical (15%), and environmental sounds (21%). In the valence category 4 ("do not like"), pop was less disliked than jazz (14%). Finally, for valence category 5 ("do not like at all"), environmental sounds were disliked more than jazz (36%), pop (29%) and classical (27%).

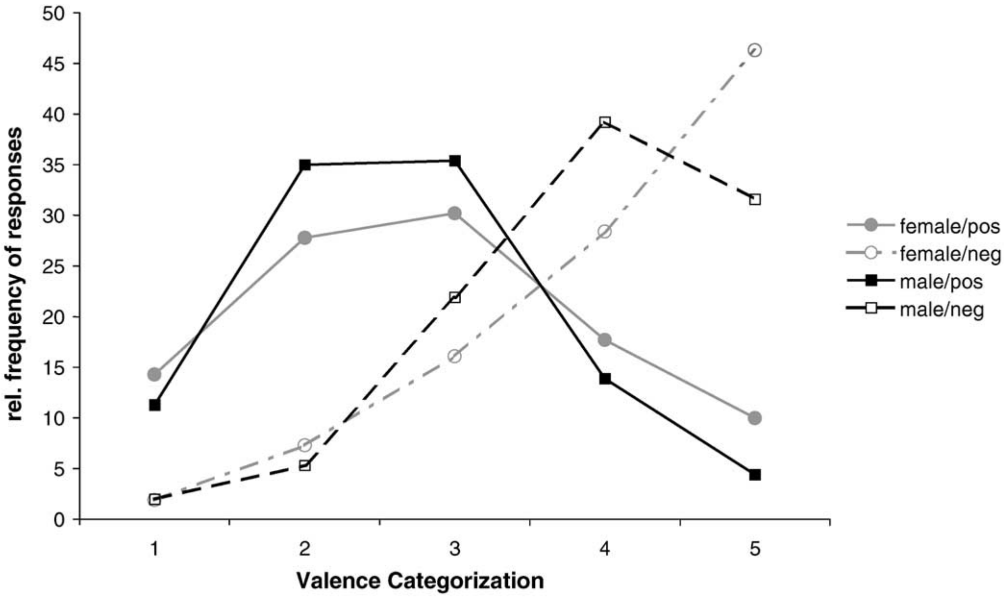
In Fig. 2, the categorical attributions in the four types of stimuli are depicted for all participants separated according to gender. While there was no significant interaction for gender, valence and musical type, there was a significant interaction between gender and valence ratings ($P < 0.05$). Simple effects analysis revealed a significant difference in responding to categories 4 and 5. Males rating the music group types as disagreeable than females (6%) and greater number of females rating the music group types most disagreeable (12%).

In Fig. 3, the relation between preselected valence category and actual valence categorisation is shown. As described earlier from pilot studies, stimuli were also categorised as positive or negative. In general, stimuli preselected for negative categorisation demonstrated a more decisive negative response compared to stimuli designed for positive attribution. This categorisation is consistent with valence ratings, as shown by the significant interaction between positive and negative classification with valence ratings ($P < 0.001$). Simple effect analysis was employed to investigate the interaction further. Valence categories 1 ("like very much"), 2 ("like") and 3 ("undecided") had significantly higher percentage of responding in the positive direction than negative (8, 21 and 14%, respectively). Additionally, for valence categories 4 ("do not like") and 5 ("do not like at all"), negative responses were more frequent than positive (11 and 32%, respectively).

3.2. Brain activation patterns

Since the main interest of the study focussed on the relation of brain activation patterns to emotional valence categorisation, EEG data recorded during stimuli eliciting positive valence judgement (categories 1 and 2) and during stimuli eliciting negative valence judgement (categories 4 and 5), respectively were averaged and analysed. EEG data recorded during neutral valence judgement (category 3) were excluded from further analysis.

Music and sound processing produced a widespread bilateral activation mainly over the anterior parts of the cerebral cortex. Maximal amplitudes were recorded over frontal and temporal areas of both hemispheres (Fig. 4). When comparing brain activation patterns during positive or negative attribution, a clear lateralisation effect emerged. In both female and male participants, positive categorisation was accompanied by a more pronounced lateralisation towards left fronto-temporal brain regions. This brain activation pattern is mainly due to a decrease of activation over right fronto-temporal areas when participants were listening to music they liked. On the other hand, negatively categorised



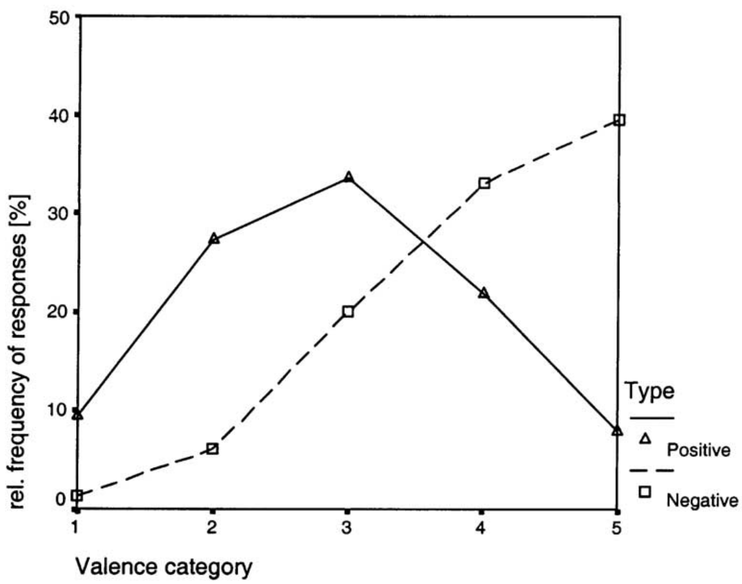


Fig. 3. Emotional valence attributions of positive or negative stimuli for all types of musical category are shown. It can be noted that the stimuli were successful in evoking the opposite emotions. The analysis of brain activation patterns was based on the actual individual's response and not on the preselection.

music produced a clearly more pronounced activation of right anterior brain regions. For the neutral condition, topography of brain activation showed a bilateral, fronto-temporal pattern without dominance of either hemisphere.

The main results of the statistical analysis on the electrophysiological data can be summarised as follows: There were highly significant main effects for "valence categorisation" ($P < 0.0001$), "gender" ($P < 0.001$), "electrodes (32 levels)" ($P < 0.001$), and "laterality" (10 electrode pairs on either side of hemisphere) ($P < 0.01$). "Stimulus" produced no significant main effect ($P = 0.07$).

There was a significant gender interaction with valence categorisation and electrodes ($P < 0.01$). This interaction is explained by more widespread valence-related differences in female participants, including frontal, fronto-temporal and fronto-central regions (F7/8, $P < 0.05$; F3/4, FT7/8, FC3/4, C3/4, each $P < 0.001$). In contrast, in male participants lateralisation differed only over anterior fronto-temporal regions, thus including only a circumscribed cortical area (F7/8, FT7/8, each $P < 0.001$).

Interhemispheric contrasts (left hemisphere versus right hemisphere) were conducted on positive and negative categorisations (Fig. 5). Positive emotions produced a clear lateralisation to the left side (female: F7/8, $P < 0.05$; F3/4, FC3/4, C3/4, each $P < 0.001$; male: F7/8, FT7/8, each $P < 0.001$), negative emotions evoked a right-sided

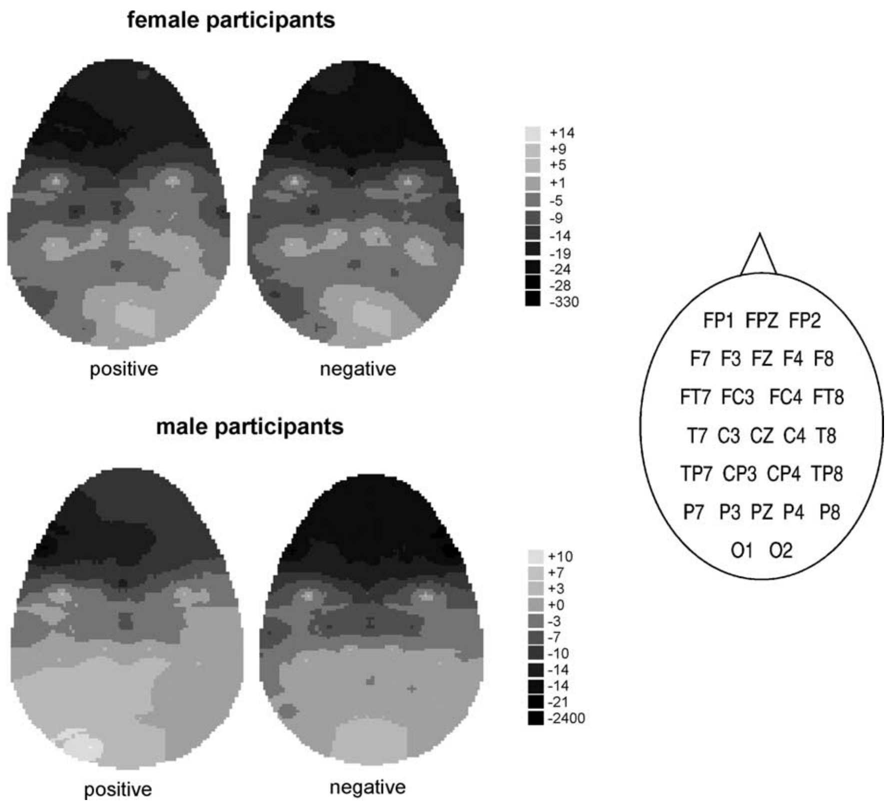


Fig. 4. Cortical dc-activation patterns, depicted from above (frontal regions at the top, occipital at the bottom). Mean dc-potentials are averaged between 10 and 12 s after stimulus start, separately for positive (left side) or negative (right side) categorisation and for female (upper row) and male (lower row) participants. Note different scaling of microvolt values due to the greater overall activation in females students. Increasing darkness of scaling is related to increasing negative dc-shift, which corresponds to increasing activation of cortical areas. The activation patterns demonstrate an extended bilateral activation, increasing from the posterior to the anterior regions of the cortex. Positive classification leads to a lateralisation towards the left hemisphere whereas negative attributions tend to a more bilateral activation pattern with a slight right-sided preponderance.

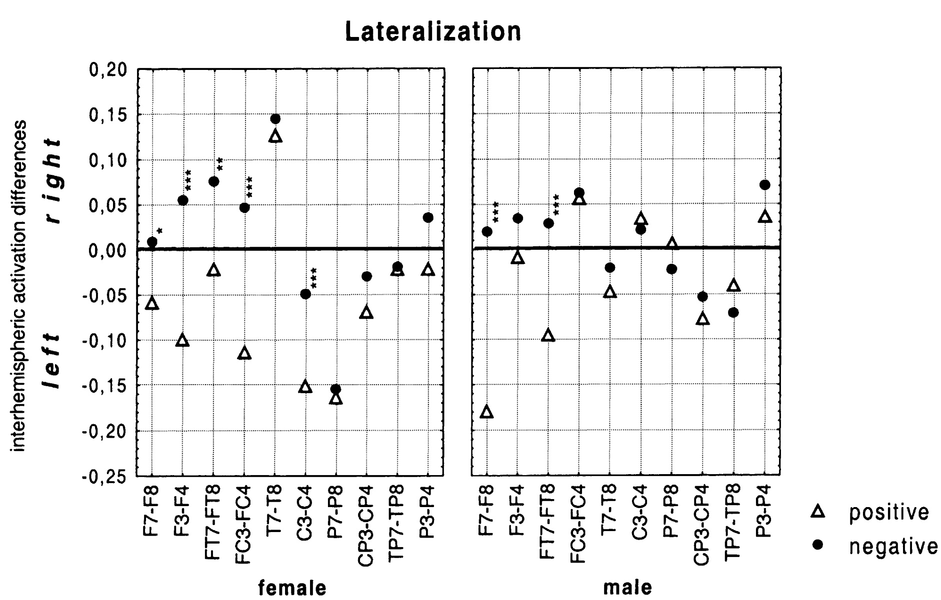


Fig. 5. Lateralisation data calculated for the normalised data set and separated for female and male participants. On the *y*-axis, the relative preponderance of activity of both hemispheres is depicted. Negative values indicate left-hemispheric and positive values right-hemispheric preponderance. On the *x*-axis, the electrode locations of homologous pairs of electrodes are shown. The anterior part of the cortex is at the left, the posterior at the right of either scale. Data for 'positive' emotions are symbolised by empty triangles, negative by filled circles. Significant lateralisations are marked with asterisks ($^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$).

preponderance (female: F3/4, FT7/8, C3/4, each $P < 0.05$; male: FT7/8, $P < 0.05$). Emotion-related differences emerge almost exclusively over frontal, fronto-temporal, and central brain areas. While negative emotions yield almost bilateral symmetrical activation patterns in anterior brain regions, positive emotions produce a left-hemispheric lateralisation. Furthermore, it is evident that the effects are more pronounced in female than in male participants.

Restriction of the analysis purely to the music excerpts (inclusion of pop, jazz and classical music but exclusion of the environmental sounds) did not change the statistical results concerning the activation asymmetries.

4. Discussion

The aim of the present study was to gain further insights into brain mechanisms during processing of emotions induced by listening to complex auditory stimuli. Musical excerpts and environmental sounds were chosen to elicit a strong emotional response. The intensity of this response was assessed indirectly by asking the participants for valence judgements after each stimulus presentation. Due to the necessity of averaging brain potentials, 160 stimuli were required. Average sound pressure levels, known to be critical for dc-EEG responses [14], were kept constant. However, similar to experiments using visual stimuli such as faces to elicit emotions (e.g. [8]) other physical parameters of the stimulus material varied.

The predictions on valence judgements, based on the results of the pilot studies were consistent with judgements from the participants. Stimuli preselected for negative categorisation produced a more decisive negative response in judgement compared to stimuli designed for positive attribution. There were gender differences in categorical attribution with males making more "dislike" judgements, and females making more "dislike immensely" judgements when listening to the respective stimuli. It should be noted that in line with the existing literature, pop music produced more frequently positive attribution compared to jazz and classical music [6,7]. However, in accordance with LeBlanc's theory of "open-earedness" of youths, the differences between the three music styles are surprisingly small [30].

The brain activation data presented here demonstrate that positive or negative emotional valence attributions to music or environmental sounds are accompanied by characteristic differences in cortical brain activation patterns. Positively attributed auditory events produced a more pronounced lateralisation towards the left fronto-temporal cortices in both male and female participants, whereas negative attribution was related to a more symmetrical bilateral fronto-temporal activation pattern. Although emotional valence attributions cannot simply be taken as "emotions" itself, these judgements are closely linked to the emotions felt during listening. In this context, it should be mentioned that the relationship between music preference and underlying subjective emotional state is not completely straightforward. For example, it is possible to have a strong affinity for musical compositions that induces a profound feeling of sadness to the listener. In this instance, a negative subjective emotional state gives rise to a positive valence attribution. However, the attitude and preference for these kinds of dissociations seem to be much less likely in adolescents compared to adults (for a review on this topic, see [21]).

The present results are consistent with Heilman's model [22], which suggests that the left frontal lobe is related to positive and the right frontal lobe to negative emotions. There is a considerable body of neuropsychological and psychophysiological data supporting this assumption, reviewed by Davidson [15]. During listening to music, further evidence for Heilman's model has been demonstrated recently using behavioural measures [18]. However, there are many contradictory data concerning the neuronal correlates of emotions. Most information has been obtained using emotional responses during viewing of pictures or perception of odours inducing affective responses [8,17,29,45,46,48]. Up to now, these imaging studies failed to demonstrate a clear-cut lateralisation effect related to different emotions.

In the auditory domain, Blood et al. [9] did not reveal any emotion-related hemispheric lateralisation effect. This discrepancy to the present study could be ascribed to methodological reasons. That is, the authors used computerised piano-melodies with increasingly dissonant harmonisation. One reason for the lack of a neo-cortical lateralisation could be that the stimuli were not pleasant enough to produce the intense positive feelings "real" music does.

There are more fundamental arguments, which may account for discrepant results when comparing functional brain imaging studies to electrophysiological measures. When examining the various effects of emotional processing on cortical activation patterns following stimulation in the visual, olfactory and auditory modality, it emerges that these effects are highly specific to modality and task, relatively weak and inter-individually variable. In this context, it is important to differentiate between studies trying to evoke emotions—as realised in the present work—and studies requiring the "identification" of emotions, since the latter declarative cognitive process does not necessarily lead to the experience of these emotions as one's owns. For valence judgement, the individual's biography, related to past emotional experiences, and internalised cultural conventions might produce a highly individual associative network accounting for additional variance when measuring cortical activation patterns during processing of emotions [2].

The lateralisation patterns related to positive or negative emotions during music and sound processing revealed an asymmetry. Positive emotions produce a pronounced lateralisation towards the left hemisphere, while negative emotions induced not to the same extent lateralisation towards the right hemisphere. Two arguments can explain this bias towards left-hemispheric preponderance in the lateralisation data. First, it is possible that in both types of stimuli participants produced "inner speech", which could be related to more or less "preconscious" comments accompanying the actual evaluation of the stimuli. "Inner speech" has been related to analytical music listening [1,5] and it is not uncommon that these cognitive processes are not reported as a conscious act by the participants [1].

Secondly, positive emotions are frequently understood as secondary, "learned" emotions, experienced in particular in social contexts, whereas negative emotions as "primary", innate emotions are associated with anxiety and defence: they are not communicative. It is possible that the communicative and thus linguistic context of positive emotions produces a co-activation of left-hemispheric language areas, thus resulting in an amplification of left-hemispheric activation [11,26].

Comparing female and male participants, the emotion-induced asymmetry included considerably larger areas in females compared to males. One could argue that female students might possess a greater openness and extent of variation for emotional experience when processing acoustic stimuli than males. The results of the valence ratings, demonstrating in females less frequently indifferent judgements and more frequently dislike as compared to males can be interpreted in this direction and could—in agreement with Heilman's model—explain the more pronounced left-hemispheric activation. From the literature, supporting [20] as well as contradictory data [40] concerning greater emotional resonance in female adolescents exist. These gender differences are not accounted for by increased arousal [23], as neither the current study, nor previous results showed a right temporal parietal increase.

A surprising finding was the lack of significant differences in activation patterns elicited by the four stimulus categories. To our knowledge up to now there is no comparable study including different styles of music and environmental sounds. This would suggest that the actual auditory brain activation patterns are determined by their affective emotional valence rather than by differences in acoustical structure. In this context, it is important to note that any acoustic stimulation using complex sounds over more than a second will produce widespread activation not only in primary and secondary auditory fields, but also in the auditory association areas and the frontal lobes [4,38,47]. Minor differences in neuronal activation patterns due to different stimulus categories and particularly to differences in the physical properties of music and environmental sounds therefore can be masked by the overall reaction of the cortex involved in processing of auditory information. This is especially the case, when attention is not directed to the identification of the stimulus or other stimulus properties but to feelings perceived during listening. The dependency of brain activation patterns on the task imposed while listening has been demonstrated several times. For example, when presenting melodies and asking the participants either to reverse them mentally or to compose a continuation, a contrasting activation pattern emerged [5]. The mental reversal task produced stronger right-hemispheric activation compared to the composition task during listening to the same melodies. Therefore, it is proposed that both, masking effects and attentional direction towards the inner feelings contribute to the observed similarity in brain activation patterns during listening to different complex auditory material.

5. Conclusion

Emotional valence judgements during listening to music and to environmental sounds were accompanied by specific brain activation patterns. Positive emotions were related to a preponderance of left frontal activation whereas negative emotions resulted in a more bilateral fronto-temporal activation with preponderance of the right hemisphere. The results are an important step in understanding the organisation of emotional behaviour during music listening and are in line with a model of hemispheric specialisation concerning perceived positive or negative emotions proposed by Heilman [22].

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Appendix A. List of music examples—duration of each excerpt 15 s

A.1. Jazz, presumed "positive" valence category

1. Nocturno (Laurindo Almeida).
   From: Stan Getz, Joao Astro Gilberto, Laurindo Almeida u.a., Sarabandes Soe, 1992.
2. Samba dees days (Stan Getz).
   From: Stan Getz, Joao Astro Gilberto, Laurindo Almeida u.a., Sarabandes Soe, 1992.
3. New Orleans stamp (Chris Barber).
   From: Chris Barber u.a., Everybody knows.
   Laser, 1985.
4. Wonderful tonight.
   From: Albert Mangelsdorff and Members of Klaus Lage Band, Rooty Toot.
   Dino Music, 1990.
5. Twist in my sobriety.
   From: Albert Mangelsdorff and Members of Klaus Lage Band, Rooty Toot.
   Dino Music, 1990.
6. Au privave.
   From: Charlie Parker, Bird on Verve, Vol. 5.
   Verve, 1951/Polydor, 1984.

7. Wish I knew.
   From: John Coltrane Quartett, Ballads.
   MCA, 1963.
8. Take five.
   From: Dave Brubeck, We're all together again for the first time.
   Atlantic, 1973.
9. Back to my roots again.
   From: Louisiana Red, Back to the roots.
   CMA, 1992.
10. Blues for Yolande.
   From: Coleman Hawkins, Ben Webster, Coleman Hawkins encounters Ben Webster.
   Verve, 1959.
11. Are you going with me?
   From: Pat Metheny, Pat Metheny Group Travels.
   ECM, 1983.
12. Chinq Miau.
   From: Yussef Lateef, Blues for the Orient.
   Prestige, 1964.
13. Part IIb.
   From: Keith Jarrett, The Köln Concert.
   ECM, 1975.
14. Jaybone.
   From: Jackson, Johnson, Brown, and Company.
   Pablo, 1983.
15. Jumpin' Blues.
   From: Jackson, Johnson, Brown, and Company, ohne Titel.
   Pablo, 1983.
16. Rosita.
   From: Coleman Hawkins, Ben Webster, Coleman Hawkins encounters Ben Webster.
   Verve, 1959.
17. Shine on harvest moon.
   From: Coleman Hawkins, Ben Webster, Coleman Hawkins encounters Ben Webster.
   Verve, 1959.
18. Quiet nights of quiet stars.
   From: The Oscar Peterson Trio, We get requests.
   MGM, 1965.
19. The girl from Ipanema.
   From: The Oscar Peterson Trio, We get requests.
   MGM, 1965.
20. Winelight.
   From: Grover Washington Jr., Winelight.
   Elektra, 1980.

A.2. Jazz, presumed "negative" valence category

1. Echoes of Harlem.
   From: United Jazz Rock Ensemble, Na endlich.
   Mood-Records, 1992.
2. Book of ways, No. 15.
   From: Keith Jarrett, Book of ways.
   ECM, 1987.
3. Bird calls.
   From: Charlie Mingus, Ah Um.
   CBS, 1959.
4. Over the rainbow.
   From: AM 4, ... and she answered.
   ECM, 1989.
5. Triple trip.
   From: Albert Mangelsdorff Quartet, Live in Tokyo.
   Enja, 1971.
6. Samba Mafiosa.
   From: Kölner Saxophon Mafia, Live.
   Jazz Haus Musik, 1982.
7. Globetrotter.
   From: No idea of time.
   Red Record, 1984.
8. Book of ways, No. 10.
   From: Keith Jarrett, Book of ways.
   ECM, 1987.
9. Dr. Ernesto.
   From: Kölner Saxophon Mafia, Live.
   Jazz Haus Musik, 1982.
10. Accidental meeting.
   From: Albert Mangelsdorff, Trilogue live.
   MPS, 1977.
11. And she answered: "When you return ...".
   From: AM 4, ... and she answered.
   ECM, 1989.
12. Rip off.
   From: United Jazz Rock Ensemble, Live opus sechs.
   Mood, 1984.
13. Frilly Bobro.
   From: Barbara Thompson, Paraphernalia.
   MCA, 1980.
14. Aus dem Hut.
   From: Albert Mangelsdorff, Purity.
   Mood, o.J.
15. On the wing again.
   From: John Surman, Such winters of memory.
   ECM, 1983.
16. Aida.
   From: Miles Davis, The man with the horn.
   CBS, 1981.
17. Round about midnight (Thelonius Monk).
   From: 20 géants du piano jazz.
   Verve, 1976.
18. Experimental jazz (Broadcast-recording, 1995).
19. Springsville.
   From: Miles and Quincey, Live at Montreux.
   Warner, 1993.
20. Caravan.
   From: Coleman Hawkins, Body and Soul.
   ITM, 1988.

A.3. Pop, presumed "positive" valence category

1. In D Street.

From: Ellen Mc Ilwaine, Looking for trouble.
Cuppamore, 1987.
2. I think, it's going to work out fine.
From: Ry Cooder, Bop till you drop.
Warner Bros., 1979.
3. Railroad worksong.
From: Notting Hillbillies, Missing.
Phonogram, 1990.
4. Sail away.
From: Rick Roberts, Windmills.
A & M, 1972.
5. Machu Picchú.
From: Siggy Schwab, Rondo a tre.
Melos Musik, 1983.
6. Love scene (Jerry Garcia).
From: Soundtrack to "Zabriskie Point".
CBS, 1970.
7. Tubular bells.
From: Mike Oldfield, Tubular bells.
Virgin, 1973.
8. From Tulsa to North Carolina.
From: Link Wray, Beans and fatback.
Virgin, 1973.
9. Going home, theme of the Local Hero (Mark Knopfler).
From: Soundtrack to "The Local Hero".
Phonogram, 1982.
10. Tripe face boogie.
From: Little Feat, Waiting for Columbus.
Warner Bros., 1978.
11. Child in time.
From: Deep Purple, Deep Purple in rock.
Electrola, 1970.
12. Beans and fatback.
From: Link Wray, Beans and fatback.
Virgin, 1973.
13. Water Boy.
From: Link Wray, Beans and fatback.
Virgin, 1973.
14. Superstition.
From: Steevie Ray Vaughan, Live alive.
Epic, 1986.
15. When the smoke is going down.
From: Scorpions, Gold ballads.
EMI, o.J.
16. Codine.
From: Man, Maximum darkness.
United Artists, 1975.
17. Diavolo rosso.
From: Paolo Conte, Concerti.
Ariola, 1989.
18. Tough kid.
From: Mitch Ryder, Live talkies.
Ariola, 1989.
19. Comfortably numb.
From: Pink Floyd, The wall.
EMI, 1979.
20. Variations on the Kanon by Johann Pachelbel.
From: George Winston, December.
Windham, 1982.

A.4. Pop, presumed "negative" valence category

1. Death Metal (Broadcast-recording, 1995).
2. Speed Metal (Broadcast-recording, 1995).
3. Boys don't cry.
From: Tekno Mafia, Same.
Motor Music, 1996.
4. If six was nine (Jimmy Hendrix).
From: Soundtrack to "Easy Rider".
Columbia, o.J.
5. Asian rebel (Suns of Aqua).
From: Wilo Paarty Sounds, Vol. 1.
Trance, 1988.
6. Amok.
From: Torment, without title.
Remedy, o.J.
7. Welche Werdi.
From: Endstadium, without title.
Ken Mehlen, o.J.
8. The happiest days of my life.
From: Pink Floyd, The wall.
Electrola, 1979.
9. Just a second.
From: Faust IV, Faust.
Virgin, 1973.
10. Robot age.
From: Slime, without title
Modern Music, 1983.
11. Speed king.
From: Deep Purple, Deep Purple in rock.
Electrola, 1970.
12. Tubular bells.
From: Mike Oldfield, Tubular bells.
Virgin, 1973.
13. Kein Bestandteil sein.
From: Einstürzende Neubauten, 5 auf der nach oben offenen Richterskala.
What's so funny about, 1987.
14. Hard lovin' man.
From: Deep Purple, Deep Purple in rock.
Electrola, 1970.
15. Somewhere over the rainbow (Marusha).
From: Bravo hits. Best of '94.
Warner Bros., 1994.
16. Computerliebe (Das Modul).
From: Bravo Hits '95.
EMI, 1995.
17. Children, guitar mix.
From: Robert Miles, Children.
Deconstruction, 1996.
18. Would the Christians want five minutes? The lions are having a draw.

From: Man, Man 1970.
Sunset, 1971.

19. Would the Christians want five minutes? The lions are having a draw.
From: Man, Man 1970.
Sunset, 1971.
20. Cash down never never.
From: Richard Thompson, Daring adventures.
Polygram, 1986.

A.5. Classical music, presumed "positive" valence category

1. Chopin, Frédéric: Scherzo No. 1.
Claudio Arrau, Piano.
Philips, 1985.
2. Schubert, Franz: String Quintett. 2. Movement (Adagio).
Heinrich Schiff, Violoncello. Alban Berg Quartett.
EMI, 1983.
3. Vivaldi, Antonio: Le Quattro Stagioni. L'inverno.
Roberto Michelucci, Violine. I Musici.
Philips, 1970.
4. Mozart, Wolfgang Amadeus: Fantasy for piano c-minor.
Käbi Laretei, Piano.
ATR, 1978.
5. Anonymus: Zouch, his march.
James Taylor, Guitar.
Decca, 1976.
6. Beethoven, Ludwig van: 4. Piano concerto. 1. Movement (Allegro moderato).
Claudio Arrau, Piano. Staatskapelle Dresden, Sir Colin Davis.
Philips, 1986.
7. Galuppi, Baldassare: Sonate No. 5, C-Major.
Arturo Benedetti Michelangeli, Piano.
Decca, 1965.
8. Balbastre, Claude-Benigne: La d'Héricourt.
Gustav Leonhardt, Hapsichord.
EMI, 1981.
9. Bach, Johann Sebastian: Toccata and Fugue d-minor.
Rudolf Reuter, Organ.
Dahringhaus und Grimm, 1990.
10. Scarlatti, Domenico: Sonata E-Major, K 162.
Christian Zacharias, Piano.
EMI, 1979.
11. Haydn, Joseph: Symphony No. 6. 1. Movement (Adagio–Allegro).
The Hanover Band, Roy Goodman.
Hyperion, 1991.
12. Dvorak, Anton: Symphony No. 9. 4. Movement (Adagio–Allegro molto).
Concertgebouw Orchester Amsterdam, Antal Dorati.
Philips, o.J.
13. Mozart, Wolfgang Amadeus: Concerto for Violin and Orchestra No. 3 G-Major. 1. Movement (Allegro).
Soloists of Moscow, David Oistrach., Olek Kagan, Violins.
Eurodisc, 1970.
14. Händel, Georg Friedrich: Firework music. Menuett No. II.
Slovak Philharmonic Orchestra, Oliver Dohnanyi.
GMS, o.J.
15. Schubert, Franz: Symphony No. 5. 1. Movement (Allegro).
Berliner Philharmoniker, Karl Böhm.
Deutsche Grammophon, o.J.
16. Mozart, Wolfgang Amadeus: Piano quartet E-flat Major. 1. Movement (Allegro).
Leygraf Quartett.
Telefunken, o.J.
17. Bruckner, Anton: Symphony No. 5. 4. Movement (Finale, Adagio).
Berliner Philharmoniker, Herbert von Karajan.
Deutsche Grammophon, 1977.
18. Wagner, Richard: Die Walküre. III. Akt.
Orchester der Bayreuther Festspiele, Pierre Boulez.
Philips, 1981.
19. Schumann, Robert: Piano quartet E-flat Major.
Glenn Gould, Piano. Members of the Julliard Quartetts.
Sony Music, 1969.
20. Bach, Johann Sebastian: Partita for Violin solo No. 2 d-minor. Chaconne.
Henryk Szeryng, Violin.
Deutsche Grammophon, o.J.

A.6. Classical music, presumed "negative" valence category

1. Dutilleux, Henri: Concerto for Violoncello and Orchestra.
Mstislaw Rostropowitsch, Violoncello. Orchestre de Paris, Serge Baudo.
EMI, 1975.
2. Dutilleux, Henri: Regard.
Orchestre de Paris, Serge Baudo.
EMI, 1975.
3. Antheil, George: Ballet Mécanique.
Reinbert de Leeuw, Piano. Niederländisches Bläserensemble, Reinbert de Leeuw.
Telefunken, 1977.
4. Hummel, Franz: Blaubart.
Edition Theater am Turm, Bernhard Lang.
TAT, 1984.
5. Boucourechliev, André: Archipel VB. Première Version (1971).
Elisabeth Chojnacka, clavecin. From: Clavecin d'aujourd'hui.
Erato, 1977.
6. Ferrari, Luc: Musique socialiste? Ou programme commun pour clavecin.

Elisabeth Chojnacka, clavecin. From: Clavecin d'aujourd'hui.
Erato, 1977.

7. Nono, Luigi: Fragmente–Stille, An Diotima.
La Salle Quartett.
Deutsche Grammophon, 1986.
8. Messiaen, Olivier: La Nativité du Seigneur. Les Anges (Nr. 6).
Almut Rößler, Organ.
Schwann, 1971.
9. Webern, Anton: Streichquartett op. 28.
Juillard Quartet.
CBS, 1978.
10. Constant, Marius: 14 Stations pour percussion et six instruments. Véronique (Nr. VI).
Sylvio Gualda, percussion. Solistes de l'Ensemble Ars Nova.
Erato, 1970.
11. Constant, Marius: Stress pour trio de jazz, piano, quintette de cuivres et percussion.
Écrit en collaboration avec Martial Solal.
Martine Solal, piano jazz, u.a. Ltg. Marius Constant.
Erato, 1970.
12. Schoenberg, Arnold: Phantasie für Violine und Klavier op. 47.
Yehudi Menuhin, Violine. Glenn Gould, Klavier.
Sony Music, 1992.
13. Boulez, Pierre: Le Marteau sans Maître: Avant 'l'artisan furieux'.
Ensemble Musique vivante. Ltg. Pierre Boulez.
CBS, 1985.
14. Scelsi, Giacinto: Quattro pezzi per orchestra. Nr. 1.
Orchestre de la Radio-Télévision de Cracovie.
Accord, 1989.
15. Antheil, George: Violinsonate Nr. 2.
Vera Beths, Violine. Reinbert de Leeuw, Klavier.
Telefunken, 1977.
16. Boulez, Pierre: Pli selon pli: Improvisation sur Mallarmé I.
Ensemble Musique Vivante. Ltg. Pierre Boulez.
CBS, 1985.
17. Hétu, Jacques: Variations pour piano op. 8.
Glenn Gould, Piano.
Sony Music, 1992.
18. Boulez, Pierre: Sonatina for Flute and Piano.
Karlheinz Zoller, Flute,
Aloys Kontarsky,
Piano.
EMI, o.J.
19. Berio, Luciano: Sequenza for Flute solo.
Karlheinz Zöller, Flute.
EMI, o.J.
20. Constant, Marius: 14 Stations pour percussion et six instruments. Simon (Nr. 5).
Sylvio Gualda, percussion. Solistes de l'Ensemble Ars Nova.
Erato, 1970.

A.7. Environmental sounds, presumed "positive" valence category

The examples nos. 4–7, 10–17 and 20 are taken from Sound Ideas. Sound effects library. Series 2000. WDR/Sound Ideas, 1987.

The examples nos. 1–3, 8, 9, 18 and 19 are taken from Echoes of Nature. Laser 1992.

1. Morning songbirds
2. Ocean waves
3. Morning songbirds
4. Water, sea shore, sea gulls, waves coming in
5. Water, splash; pebbles into stream
6. Wind and shutter banging
7. Ocean waves
8. Morning songbirds
9. Morning songbirds
10. Leaves, footsteps: shore, slow
11. Cat, lapping up milk
12. Walking through leaves
13. Indoor fireplace: crackling popping
14. Motor cycle, 1200 ccm, start
15. Ship's horn
16. Clock, striking 12
17. Billiard room, atmosphere
18. American wilds
19. Frog chorus
20. Waves coming in, spray, medium

A.8. Environmental sounds, presumed "negative" valence category

The examples nos. 2–10 are taken from a series of industrial noises: Oldenburger Industriegeräusche. Oldenburg, 1988.

The examples nos. 1, 13, 17–19 are taken from Sound Ideas. Sound effects library. Series 2000. WDR/Sound Ideas, 1987.

The examples nos. 11, 12, 14–16 and 20 are taken from a Test-CD: Fono-Forum, SZV—Zentrallabor, 1988.

1. Cow-bell
2. Air-pressure polishing
3. CO_2-welding
4. Percussion riveting machine
5. Circular saw
6. Punched card machine
7. Lever punched
8. Fast printing machine
9. Planing machine
10. Wood shaper

11. Twin-Tone-Sweep
12. Sine-tone 1 kHz
13. Jet of water
14. Kettle, whistling
15. Sinusoidal-Burst 1 kHz
16. Square wave-sound 6.5 kHz
17. Whistling polar wind
18. Chain saw, cutting
19. Fire Arms: Machine Gun
20. Needle impulse sounds

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