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Receptive amusia: evidence for cross-hemispheric neural networks underlying music processing strategies

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Summary
Perceptual musical functions were investigated in patients suffering from unilateral cerebrovascular cortical lesions. Using MIDI (Musical Instrument Digital Interface) technique, a standardized short test battery was established that covers local (analytical) as well as global perceptual mechanisms. These represent the principal cognitive strategies in melodic and temporal musical information processing (local, interval and rhythm; global, contour and metre). Of the participating brain-damaged patients, a total of 69% presented with post-lesional impairments in music perception. Left-hemisphere-damaged patients showed significant deficits in the discrimination of local as well as global structures in both melodic and temporal information processing. Right-hemisphere-damaged patients also revealed an overall impairment of music perception, reaching significance in the temporal conditions. Detailed analysis outlined a hierarchical organization, with an initial right-hemisphere recognition of contour and metre followed by identification of interval and rhythm via left-hemisphere subsystems. Patterns of dissociated and associated melodic and temporal deficits indicate autonomous, yet partially integrated neural subsystems underlying the processing of melodic and temporal stimuli. In conclusion, these data contradict a strong hemispheric specificity for music perception, but indicate cross-hemisphere, fragmented neural substrates underlying local and global musical information processing in the melodic and temporal dimensions. Due to the diverse profiles of neuro-psychological deficits revealed in earlier investigations as well as in this study, individual aspects of musicality and musical behaviour very likely contribute to the definite formation of these widely distributed neural networks.

Keywords: amusia; music perception; auditory agnosia; cognitive processing; cerebrovascular disease

Abbreviations: b.p.m. = beats per minute; LHD = left-hemisphere damage; RHD = right-hemisphere damage

Introduction
The neural substrates underlying music information processing are not yet outlined sufficiently and the question of hemispheric specificity concerning the diverse components of music perception is still discussed controversially. It has been shown in fundamental studies that one aspect influencing hemispheric preponderance in melody perception seems to be musical expertise (Bever and Chiarello, 1974; Hirshkowitz *et al*., 1978; Altenmüller, 1986, 1989). Healthy non-musicians predominantly showed auditory activation patterns of the right frontotemporal cortex, whereas musically trained subjects revealed an additional activation of left-hemispheric auditory areas. This tendency of lateralization to the left hemisphere in professional musicians could be replicated in several investigations and was not only shown in melodic but also in rhythmic processing. It was ascribed to different cognitive strategies used by trained and untrained listeners (Beisteiner *et al*., 1994; Altenmüller and Beisteiner, 1996). These strategies presumably depend on certain principal perceptual processes concerning melodic as well as temporal information: both melodic and temporal perception are assumed to require local and global auditory information processing (Dowling, 1982). In melody processing two parameters appear to be functionally important: the particular interval between two succeeding notes, assumed to be

processed locally, and the melodic contour, requiring global information processing (Dowling, 1982; Peretz and Morais, 1987, 1993; Peretz, 1990). In comparison, the temporal dimension would include rhythm perception, i.e. the discrimination of durational values by local, analytic strategies as well as the interpretation of metre via global mechanisms of perception (Peretz, 1990). Referring to the additional left-hemispheric activation found in musically trained listeners, musical expertise leads to perceptual processes that are predominantly based on local strategies. In summary, the neuropsychological findings on music perception in healthy subjects suggest a hemispheric specificity for dissociated musical functions.

In patients suffering from unilateral brain lesions, however, a similar hemispheric dissociation of the processing of intervals and rhythm versus the processing of contour and metre could only partially be verified. In their extensive studies, Peretz and Liégeois-Chauvel and colleagues have shown the expected disturbances of interval processing along with intact contour perception in patients presenting with left hemisphere lesions; yet in right-brain-damaged patients both processing strategies turned out to be impaired (Peretz, 1990; Liégeois-Chauvel *et al*., 1998). This suggests that the global contour-processing system serves as a subsystem for embedding local interval information and is a prerequisite for decoding local stimuli. Thus, recognition of contour should precede the processing of interval, yielding a two-stage processing cascade (Dowling and Bartlett, 1981; Dowling, 1982; Peretz, 1993).

A similar dissociation of local (rhythm) and global (metre) processing in the temporal dimension has so far been elusive. While it has been assumed that recognition of metre derives from (intact) rhythmic organization, i.e. that temporal perception is based on a hierarchical system (Povel and Essens, 1985), others have discussed a model of separate levels of analysis (Lerdahl and Jackendoff, 1983; Peretz, 1990; Liégeois-Chauvel *et al*., 1998). The latter view has been supported by Peretz, who demonstrated a dissociated deficit in rhythm perception in some patients in the absence of a metre perception deficit (Peretz, 1990), and by the opposite pattern described in the study of Liégeois-Chauvel and colleagues (Liégeois-Chauvel *et al*., 1998). In addition, no clear hemispheric preponderance of temporal processing has been found: deficits in rhythm perception have been described following right-hemisphere damage (RHD) as well as left-hemisphere damage (LHD) (Mavlov, 1980; Fries and Swihart, 1990). Finally, the question of whether melodic and temporal information is processed by associated/overlapping or by separate neural networks is still controversial. However, dissociated melodic or rhythmic deficits in several patients suggest a separation of the melodic and temporal dimension at least at an early stage of the information processing course (Peretz, 1990; Peretz *et al.*, 1994).

Considering the heterogeneous patterns of deficits in brain-damaged patients, it has been suggested that musical behaviour may be based on widely distributed, but locally specialized subsystems (Judd, 1988; Sergent, 1993; Zatorre, 1993; Peretz *et al*., 1994). Furthermore, it has become evident that the brain regions involved may be influenced by task-specific aspects and may depend on the complexity of the musical stimuli, e.g. novelty of the musical material, transposition, preservation of an internal auditory representation or pitch retention (Shapiro *et al.,* 1981; Marin, 1982; Edworthy, 1985; Zatorre and Samson, 1991; Zatorre *et al.*, 1994). Moreover, non-specific generic cognitive mechanisms like attention and memory might modulate the processing of melodic and temporal structures in a task-specific question.

Thus, the cognitive organization of the neuronal networks underlying music perception and processing comprises an incompletely studied neuropsychological domain to which the present work tries to contribute via research in brain-damaged patients. Following cortical lesions, symptoms of amusia, i.e. an impairment of musical functions, are a frequent, yet frequently overlooked neuropsychological phenomenon (Samson and Zatorre, 1988; Peretz, 1990; Peretz *et al*., 1994; Liégeois-Chauvel *et al*., 1998). As in aphasia, they may present as expressive or receptive deficits, the latter being considered a subtype of auditory agnosia. These deficits often remain unnoticed since, except for active musicians, the patients may not be aware of an altered music perception, even long-term. Furthermore, a neuropsychological test battery for the evaluation of music processing, providing sufficient sensitivity yet being short enough to be carried out as a bedside test, has not, until now, been available. This certainly contributes to the lack of knowledge on music perception.

Post-lesional deficits in music perception not only comprise disturbances in processing different melodic and temporal musical structures, but can also refer to a loss of the emotional musical experience, i.e. the aesthetic enjoyment of music. Two case reports describe a dissociated loss of emotional musical qualities following right temporoparietal lesions (Mazzucchi *et al*., 1982; Mazzoni *et al*., 1993). Systematic studies concerning this type of defective perception have not yet been performed.

Detecting and assessing music perception deficits pose several difficulties: depending on the size of the lesion and the neuronal networks being affected, there may be miscellaneous types and degrees of musical impairment. Thus, a test battery has to be highly sensitive and has to cover all significant musical parameters in order not to miss subtle deficits. Since symptoms of amusia may improve with the passage of time due to short-term cerebral plasticity changes, it seems important to perform testing at an early stage of rehabilitation. In addition, in sharp contrast to language functions, musical behaviour and the standard of musicality differ widely within the population and music processing represents an extremely individual ability depending mainly on early exposure. So the real extent of musical impairments can only be assessed when classifying each patient according to his musical biography, which means the knowledge of music as well as the musical activities and musical behaviour prior to brain damage, an aspect which has frequently been neglected in previous studies.

The present study aimed at assessing the different facets of amusia at an early stage following unilateral cortical lesions due to cerebrovascular disease. Having established a sensitive test battery that can be used as a bedside test, we expected to detect even subtle disturbances of processing melodic and temporal musical stimuli that might otherwise have been missed, thus being able to assess the frequency of amusia following cortical brain damage. Additionally, tests of attention disorders were performed for relating impairments of music perception to non-specific attentional deficits. In summary, we expected to obtain further information on the neural substrates underlying music processing, the cognitive organization of the neuronal networks involved and the contribution of non-specific generic cognitive mechanisms to music processing.

Table 1 *Catalogue serving for classification according to general education, musical training and musical behaviour (modified from Reitschuster, 1993)*

I	General education and profession
II	Musical training
	(A) Active professional musician
	(B) Professional training, but infrequent performing
	(C) Non-professional training, frequent playing
	(D) Non-professional training, occasional playing
	(E) Moderate training, no practice
	(F) Little training, no practice
	(G) No training, no practice
III	Habits of listening to music
	'How often do you listen to music?'
	'On which occasions do you listen to music (e.g. in the car, at home etc.)?'
	'Which volume do you choose when listening to music?'
	'Do you prefer radio, record, CD, Walkman, TV or live music?'
IV	Habits of musical instrument playing or singing
V	Preferred type of music, favourite pieces and instruments

Methods

Subjects

Twenty patients presenting with first unilateral focal cerebrovascular brain lesions in the frontal, temporal or parietal region were selected. They were in-patients at the Department of Neurology at Hannover Medical School.

Exclusion criteria were previous stroke, disseminated neurological disease, sedating drugs, hearing impairment and major impairment of attention. Aphasic patients were only excluded if they were unable to understand the instructions. All experimental sessions for this study were performed 5–10 days post-lesion in order to minimize unspecific attentional deficits and to avoid missing receptive deficits that, as in aphasia or neglect, might already have subsided a short time after the event due to potential short-term cerebral plasticity changes.

A group of 45 volunteers served as normal controls for establishing the test battery (see below). Of these, 20 were selected as controls and were matched to the stroke patients as closely as possible according to age, sex, handedness, general education, profession and musical training. They were either in-patients at neurological or surgical wards at Hannover Medical School, suffering from peripheral neurological disease or from peripheral trauma, or they were members of the office or technical university and hospital staff, i.e. neither students nor academic staff members. Exclusion criteria for control subjects were previous central neurological disease or intake of psychoactive drugs.

Prior to testing, all brain-damaged patients underwent a complete neurological examination. Cerebrovascular lesions were evaluated by cranial CT or MRI scans. Patients, as well as matched controls, were additionally tested for unspecific attention disorders. In all subjects handedness was assessed according to Oldfield (Oldfield, 1969). All subjects participating in this study were non-musicians and were classified according to their musical training and their (prelesional) knowledge of music and musical behaviour. Table 1 shows the catalogue serving for classification (modified from Reitschuster, 1993). General education ranged from manual workers with a junior high school degree to office workers and subjects with university education.

The Ethics Committee of the Hanover Medical School approved the project and consent was obtained from all subjects participating in this study.

Test battery and procedure

Attention

Attention deficits were assessed by the following subtests of the computerized test battery for attention disorders formulated by Zimmermann and Fimm (Zimmermann and Fimm, 1993).

(i) 'Alertness': this module tests simple visual reaction time with and without an auditory warning signal.

(ii) 'Divided Attention': the scenario of this subtest contains both visual and auditory, standard and target stimuli. Subjects have to divide their attention between the modalities and press a button for target events.

(iii) 'Go–NoGo': this task assesses the ability to withhold a motor response as only a subset of the stimuli require a 'go' response.

Musical experience

The emotional musical experience was evaluated by a modified questionnaire developed by the Department of Music Psychology at the University of Music and Theatre, Hannover (see Behne, 1997). It assesses the habitual aspects of 'Musikerleben' (musical experience) using 23 questions covering the following aspects: cognitive/analytic, emotional,

Table 2 *Excerpts of the seven-category questionnaire for assessing the habitual aspects of 'Musikerleben'*

	When I listen to music . . .
Cognitive/analytic	. . . I try to grasp the structure of a piece of music (repetitions, variations)
Emotional	. . . I pay attention to what types of feelings are expressed through the music
Compensating	. . . it changes my mood
Motorical	. . . I sing along with the music
Associative	. . . I have pictorial images
Vegetative	. . . it really gets under my skin
Sentimental	. . . I like to dream

The patient had to answer 23 questions using a five-point scale, from 1 = this is exactly true for me, to 5 = this is not at all true for me (see Behne, 1997).

Table 3 *Components of receptive musical functions assessed in the test battery*

Receptive musical function	Subtest
Auditory memory function	Recognition of song melodies
Lower-level auditory information processing	Discrimination of pitch
Local auditory information processing	Discrimination of interval Discrimination of rhythm
Global auditory information processing	Discrimination of contour Discrimination of metre

compensating, motorical, associative, vegetative and sentimental (Table 2). Since the acute state of illness at the time of testing and the hospital situation certainly affected the usual 'Musikerleben', patients were asked about their prelesional practices and strategies of listening as well as about potential post-lesional alterations that might already have become obvious at this point.

Receptive musical functions

To assess different aspects of music perception a test battery was designed. To ensure exact reproducibility and precise rhythm MIDI (Musical Instrument Digital Interface) technique was employed. A piano sound was chosen since this was most likely to be familiar to all subjects. Each patient was tested individually in a single session. The test was played from a Sony DAT recorder in a quiet surrounding, using headphones of high quality (Sennheiser electronic GmbH and Co, Wedemark, Germany). The examiner marked the patients' answers on a response sheet. In order to avoid errors due to lack of concentration, testing could be interrupted whenever requested by the patient.

The test battery covered the following components of receptive musical functions within six subtests (Table 3): (i) auditory (musical) long-term memory function by testing recognition of familiar song melodies; (ii) basic auditory information processing by testing discrimination of pitch; (iii) local auditory information processing by testing discrimination of interval and rhythm; (iv) global auditory information processing by testing discrimination of contour and metre.

The single subtests were constructed as follows (Fig. 1).

Recognition of familiar song melodies. Recognition of five nursery rhyme melodies.

Discrimination of pitch. A target tone was followed by a comparison tone, which was either a major or a minor second apart or which remained the same; patients had to respond 'same' or 'different'; the experimental trials were separated by a rest of three bars in 2/4 metre. There were 24 stimuli and the tempo was 48 beats per minute (b.p.m.).

Discrimination of interval and contour. A target melody of four bars duration was followed by a rest of three quarter notes and then a comparison melody, in which either one tone was changed or remained unchanged. It was a 'same–different' discrimination task. Interval-violated and contour-violated stimuli were mixed randomly in order to avoid systematic errors. One half of the sequence was in 2/4 metre, one half in 3/4 metre. There was a rest of four bars in 3/4 metre before the next experimental trial started. There were 48 stimuli and the tempo was 104 b.p.m.

Discrimination of rhythm. A target rhythm of four bars duration played on one note (g) was followed by a rest of three quarter notes and then a comparison rhythm, in which either one bar was changed or remained unchanged. Again the task was constructed as a 'same–different' discrimination. One half of the sequence was in 2/4 metre, one half in 3/4 metre. There was a rest of four bars in 3/4 metre before the next experimental trial started. There were 24 stimuli and the tempo was 104 b.p.m.

Discrimination of metre. A melody of four bars duration was presented twice without a rest in between, thus making a sequence of eight bars. It was either a march (2/4 metre) or a waltz (3/4 metre) and subjects had to discriminate between these two types of metre. The metre was marked by a clear accentuation on the first beat of each bar. The experimental trials were separated from each other by a rest of four bars in 3/4 metre. There were 24 stimuli and the tempo was 104 b.p.m. These trials had to be supported by a melody, since in an exploratory experimental set, playing the metre stimuli on one tone turned out to be too difficult. In this set even many normal controls had failed to discriminate above chance.

Each discrimination subtest was preceded by two practice trials. Each new stimulus was introduced by a warning signal.

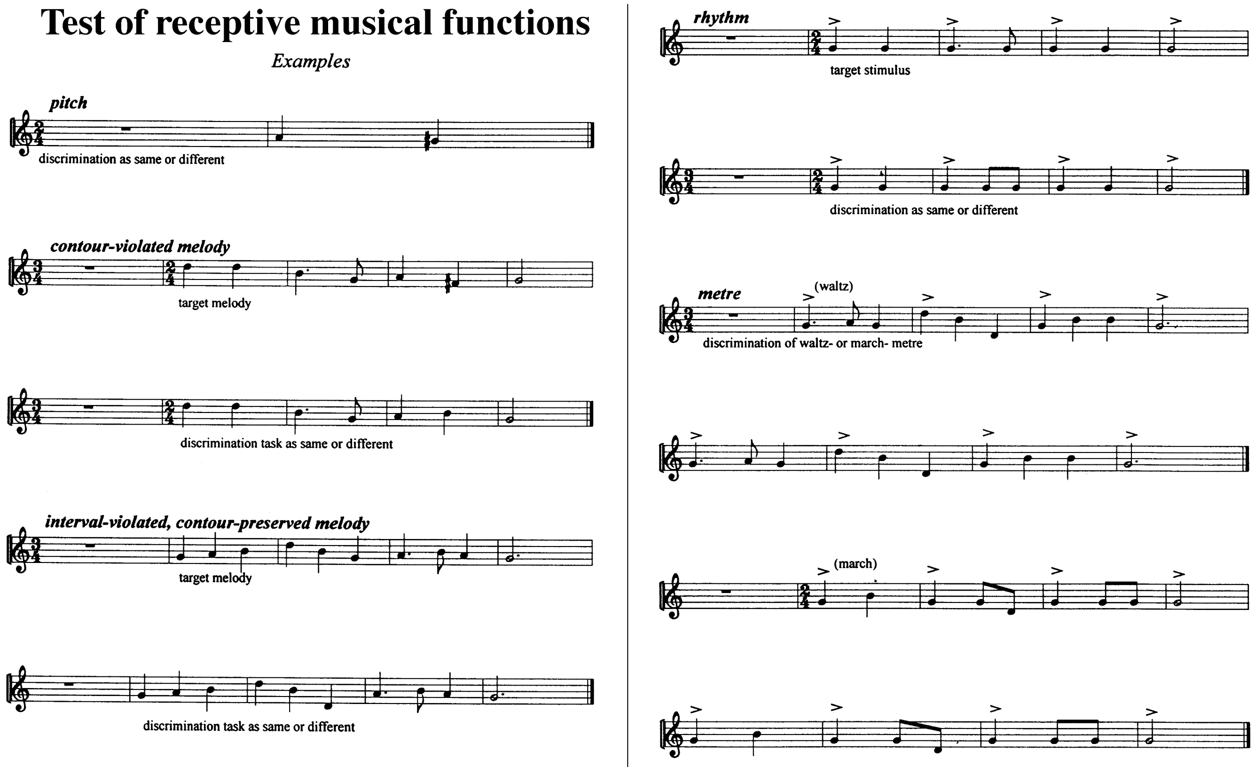

Fig. 1 Excerpts from the test of receptive musical functions.

Since the test had to be short and since it aims at the assessment of discrimination deficits, two-thirds of the stimuli were changed, whereas only one-third was unchanged in each discrimination condition. Stimuli of different degrees of difficulty were mixed randomly. Pitch discrimination was always tested first in order to rule out impairments of basic musical functions. To avoid systematic effects due to fatigue, all other subtests were performed in random order.

Administration of the test battery took 60–80 min. Thus, the test could easily be implemented in the hospital routine. Since the technical equipment is very small, testing can be performed at the bedside.

Results

Establishing the test battery

A group of 45 normal controls was tested for receptive musical functions: 24 male, 21 female; mean age = 53.4 years, SD = 11.6. Classification according to musical training (Table 1) assigned one subject to category D, five subjects to category E, six subjects to category F and 33 subjects, having experienced no musical training at all, to category G.

Melodies of well-known nursery rhymes were recognized without any deficit by all subjects. Detailed analysis of all discrimination subtests (24 stimuli each) is shown in Fig. 2: pitch discrimination, average correct responses 23.2 (SD = 1.6); discrimination of interval-violated (contour-preserved) sequences, 19.6 (SD = 1.9); discrimination of contour-violated sequences, 19.0 (SD = 2.1); discrimination of rhythm-changed sequences, 20.1 (SD = 2.0); and discrimination of metre (waltz versus march), 18.6 (SD = 2.6).

These findings reveal that, except for the pitch condition (testing basic musical functions), the discrimination subtests cannot usually be performed perfectly by non-musicians. This indicates that the results obtained on music perception abilities are not affected by ceiling effects.

To determine the reliability of the method, test–retest measurements were performed on 10 of our normal controls with several weeks between the two sessions. Test–retest correlation by ANOVA (analysis of variance) demonstrated a satisfactory retest reliability of the method, reaching significance in all experimental subtests ($P < 0.01$).

Patients

A group of 20 patients suffering from first unilateral cerebrovascular lesions and meeting the strict selection criteria was tested. Of these, eight patients had RHD (five male, three female; mean age 57.0 years, SD = 11.6, range 30–66 years) and 12 had LHD (nine male, three female; mean age 58.3 years, SD = 16.2, range 22–76 years). The majority were diagnosed with cerebrovascular infarction (18), while two patients had acute cerebrovascular haemorrhage. One patient was left-handed. Categorization according to musical training (Table 1) showed that one patient could be assigned to category D, one patient to category E, three patients to category F and 15 patients to category G.

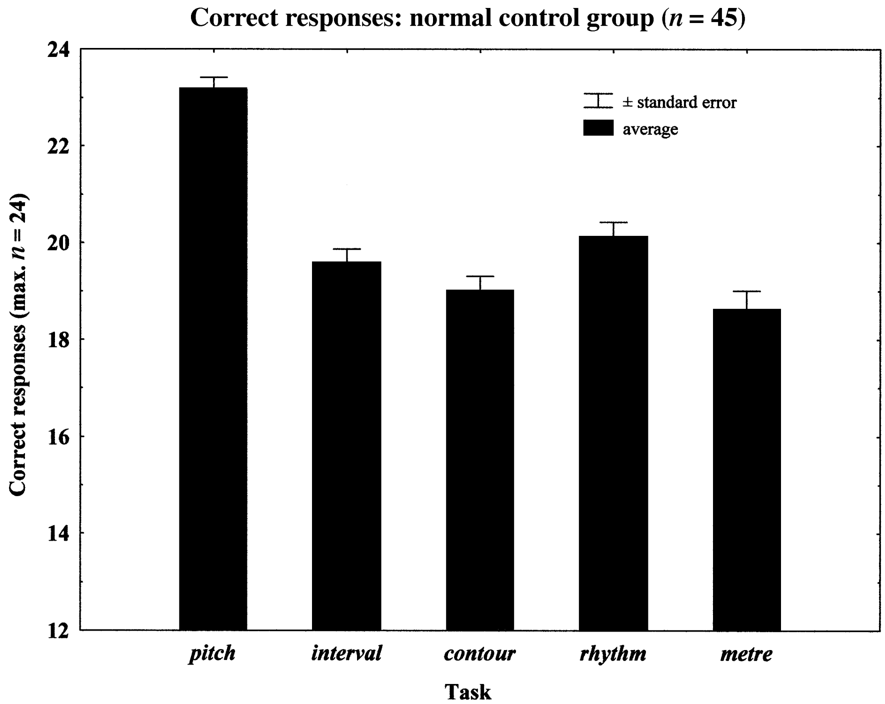

Fig. 2 Analysis of all discrimination subtests in the normal control group. Mean numbers of correct responses obtained for the discrimination of pitch, interval, contour, rhythm and metre.

The group of 20 matched controls had a mean age of 56.2 years (SD = 15.0, range 20–75 years).

Melodies of well-known nursery rhymes were recognized without any deficit by all subjects in each group, except for two patients who were of Bulgarian and Italian origin and therefore were not familiar with German nursery rhymes. Analysis of the discrimination subtests was performed separately for each group, i.e. RHD patients and their corresponding control group as well as LHD patients and their corresponding controls. Data were submitted to an ANOVA followed by contrast analysis, and to non-parametric statistical processing.

RHD patients (Fig. 3A)

Patients performed worse than controls in all subtests. One female patient (R.K.) showed an almost complete receptive amusia: she was unable to discriminate any of the changed stimuli in both melody tasks as well as the rhythm task and performed far below chance in the discrimination of pitch and metre. Therefore, this patient was excluded from statistical analysis comparing RHD patients and matched controls. Data from the other RHD patients were then processed by ANOVA. The means suggested deficits in the pitch discrimination task as well as in both melody tasks, even though differences in these conditions did not quite reach statistical significance. In the temporal organization tasks, however, RHD patients showed significant impairments. The mean number of correct responses of the patients and controls, respectively, were as follows: discrimination of pitch, 19.4 (SD = 3.3) versus 22.1 correct responses (F = 3.31, P = 0.07); discrimination of interval, 18.2 (SD = 3.8) versus 19.8 (F = 1.11, P = 0.29); discrimination of contour, 17.1 (SD = 3.4) versus 18.8 (F = 1.32, P = 0.26); discrimination of rhythm 16.4 (SD = 4.6) versus 20.0 (F = 5.73, P = 0.02); and discrimination of metre 14.6 (SD = 1.3) versus 18.7 (F = 7.71, P = 0.007). Due to the high variability, non-parametric tests were also performed on each condition. Comparison by the Mann–Whitney U test showed again that differences in the discrimination of pitch, interval and contour failed significance, whereas differences yielded a weak significance in the rhythm task (U = 9, P = 0.045) and a clear significance in the metre task (U = 1.5, P = 0.002).

LHD patients (Fig. 3B)

Again, patients showed a worse performance than the corresponding group of matched controls, reaching significance in each subtest of higher musical functions in an ANOVA, regardless of whether it assessed local or global functions. The mean numbers of correct responses of the patients and controls, respectively, were as follows: discrimination of pitch, 21.6 (SD = 2.9) versus 22.6 correct responses (F = 0.95, P = 0.33); discrimination of interval, 16.6 (SD = 2.3) versus 19.2 (F = 6.31, P = 0.01); discrimination of contour, 16.3 (SD = 2.2) versus 18.9 (F = 6.31, P = 0.01); discrimination of rhythm, 17.7 (SD = 2.7) versus 19.9 (F = 4.79, P = 0.03); and discrimination of metre, 15.7 (SD = 2.6) versus 17.7 (F = 3.78, P = 0.05). A similar pattern of significant results was yielded by the

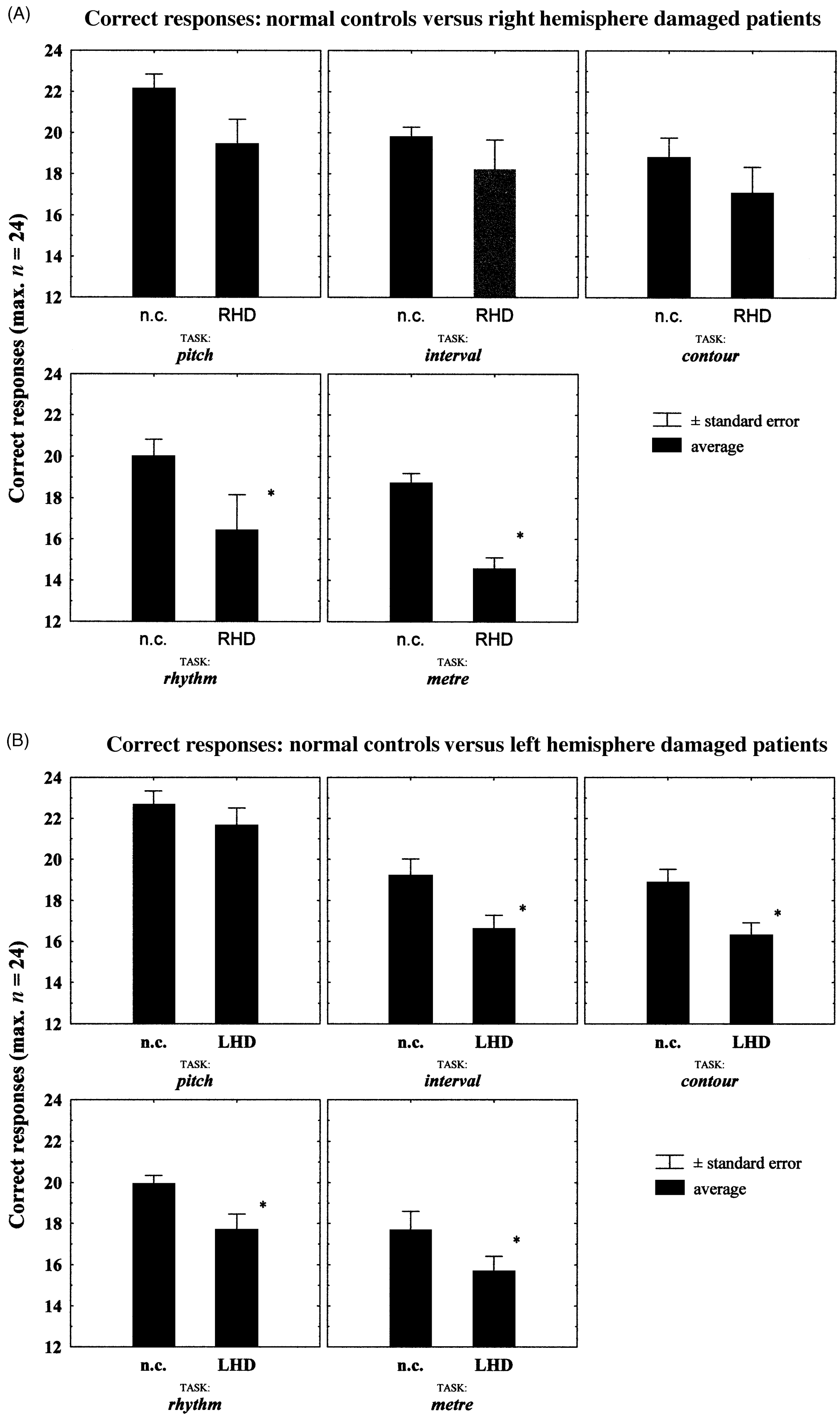

Fig. 3 Continued on facing page.

Mann–Whitney *U* test (discrimination of interval: $U = 27.5$, $P = 0.01$; discrimination of contour: $U = 29$, $P = 0.01$; discrimination of rhythm: $U = 37.5$, $P = 0.04$; discrimination of metre, weakly significant: $U = 38$, $P = 0.047$).

Due to the unequal number of patients in the RHD and LHD groups, a straight comparison between these groups would perhaps not yield valid statistics. Thus, Fig. 3C is presented here merely as a rough indication of possible differences between LHD and RHD patients.

Response pattern

In order to rule out a bias concerning the responses on changed stimuli trials (two out of three of all stimuli) or unchanged stimuli trials (one out of three of all stimuli) towards responding 'changed', response patterns in the pitch discriminations task, in both melody tasks and in the rhythm task had to be analysed *per se*. All groups, i.e. LHD and RHD patients as well as matched controls, were found to have fewer correct answers in the changed stimuli than in the unchanged stimuli in all subtests (RHD, 71.9% correct responses in changed stimuli versus 82.4% in unchanged stimuli; LHD, 74.6% versus 84.1%; normal controls, 81.6% versus 91.6%). These differences varied in size across the different tasks. They were found to be highly significant in normal controls performing the melody tasks ($F = 19.66$, $P < 0.0001$) and the pitch discrimination task ($F = 6.80$, $P = 0.01$) as well as in LHD patients performing the melody tasks ($F = 9.09$, $P = 0.004$). In RHD patients performing the rhythm task differences were close to significance ($F = 3.72$, $P = 0.06$). These findings demonstrate that the test battery design did not induce a biased response pattern towards responding 'changed'. Rather, patients were unable to recognize stimulus changes, thus exhibiting post-lesional impairments in music perception.

Frequency of amusia

In order to assess the frequency of music perception deficits in our patients we looked at the individual values obtained in each discrimination task. For a conservative estimation, the average values obtained on RHD patients and LHD patients were considered the cut-off points. This way, five patients in the RHD group (62.5%), including patient R.K., and nine patients in the LHD group (75%) were found to have signs of impairment in music processing. Two LHD patients showed deficits in only one processing domain, but five RHD and three LHD patients showed an impairment in at least three domains. Summarizing these findings, 69% of our patients presented with post-lesional symptoms of amusia.

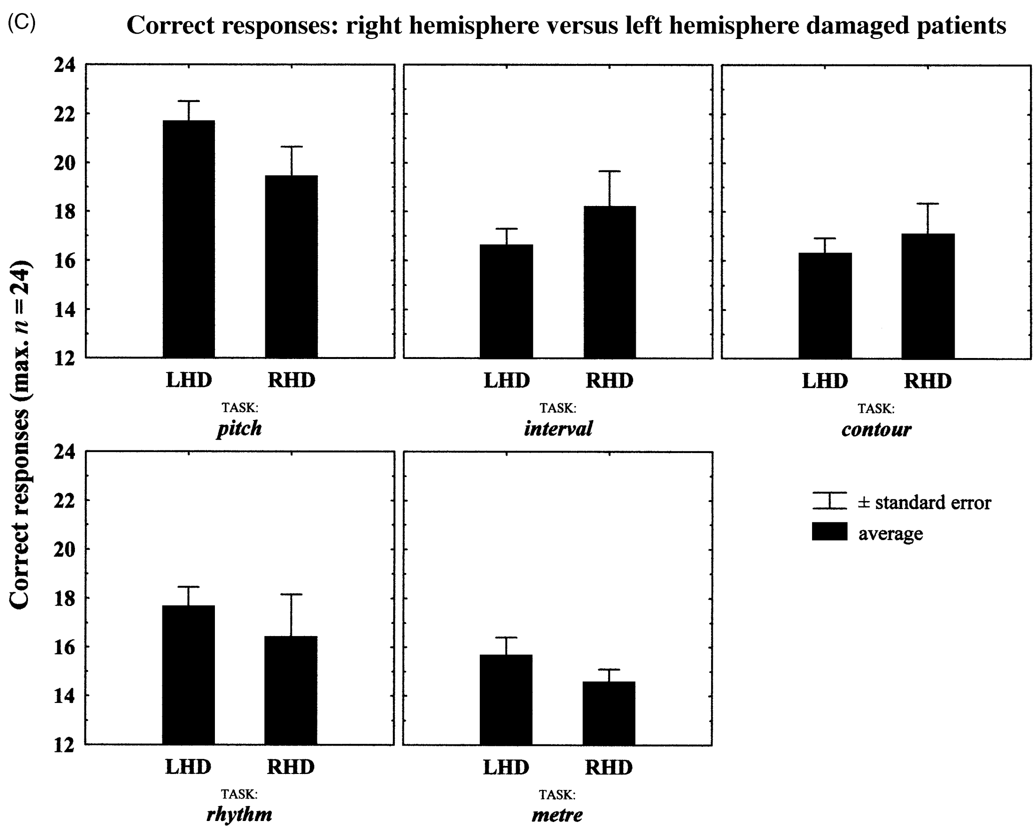

Fig. 3 Mean number of correct responses obtained for the discrimination of pitch, interval, contour, rhythm and metre. (**A**) Normal controls versus RHD patients; (**B**) normal controls versus LHD patients; (**C**) RHD versus LHD patients. * = significant differences; n.c. = normal controls.

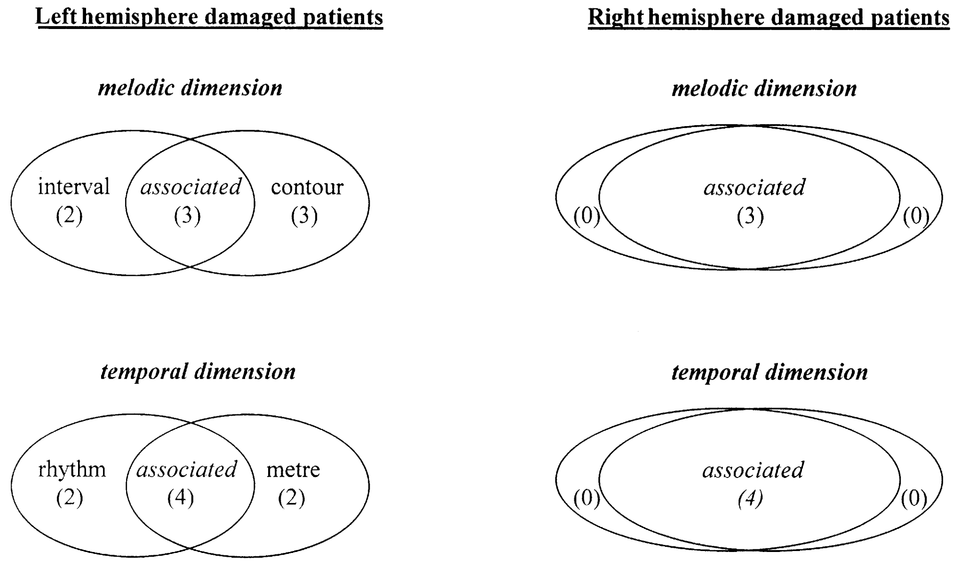

Fig. 4 Patterns of local and global deficits. Associated deficits in both global as well as local stimuli are indicated as '*associated*'.

Hierarchy of the systems

Our data were also examined with regard to a potential hierarchy of global and local processing mechanisms, i.e. recognition of global structures being a prerequisite for local information processing.

In the RHD group ($n = 8$), three patients (including patient R.K.) presented with clear deficits in interval- as well as contour-processing. One further patient (E.P.) showed deficits in the contour condition, while local interval processing was exactly average compared with the RHD group, but clearly below the average of the matched controls. In the temporal dimension (rhythm versus metre), five patients showed combined deficits in rhythm as well as in metre processing. Assuming that global processing mechanisms are mainly confined to the right hemisphere, these findings would indeed support the hypothesis that an impairment of the global processing system causes an inability of local information processing in the left hemisphere. Compared with the normal controls, no deficits exclusively in the local or in the global conditions were observed in RHD patients (Fig. 4).

Since LHD patients ($n = 12$) had unexpectedly shown significant deficits in both local as well as global conditions, this group was also further analysed with respect to potential inter-relations of the systems. In the melody condition, three patients had deficits in interval- as well as contour-processing, and in the temporal dimension four patients had a combined deficit in the perception of rhythm and metre. One patient, however, showed impaired interval-processing and two patients had exclusive rhythm-processing deficits, while the corresponding global functions were undisturbed. On the other hand, three patients presented an impairment in the discrimination of contour and two patients in the discrimination of metre, along with intact local stimuli processing. In summary, associated local and global deficits as well as exclusive local and global deficits were found in the LHD group (Fig. 4).

Association of melodic and temporal deficits

Ten patients (four RHD, six LHD) presented with combined deficits in melodic and temporal conditions, indicating an association of melodic and temporal neural networks. Two of them even demonstrated a specific impairment concerning local and global processing mechanisms: one LHD patient (G.J.) revealed a diminished ability for processing local stimuli in the melodic as well as in the temporal dimension, i.e. in interval and rhythm, while global stimulus processing was undisturbed; another LHD patient (F.B.) on the other hand was found to have impairments exclusively in both global conditions, i.e. in the processing of contour and metre. Three patients, however, had dissociated deficits in melodic or temporal conditions: one RHD patient (M.B.) presented with an impairment in the discrimination of pitch, rhythm and metre, while interval and contour conditions had remained undisturbed. Two LHD patients (C.F. and U.M.) had dissociated deficits in one of the temporal dimensions.

Site of the lesion

Patterns of receptive musical deficits were evaluated with respect to an anterior or posterior site of the lesion, i.e. with lesions being located either anterior or posterior to the central sulcus. As can be seen in Table 4, three RHD patients had suffered anterior lesions, of whom one did not show any deficits of musical functions, one (R.K.) presented with an almost complete receptive amusia and one had associated impairments in the temporal domain. Out of five patients with right posterior lesions, two had no receptive deficits,

Table 4 *Clinical data on brain-damaged patients*

Patient	Age	Sex	Side of lesion	Site	Receptive musical deficits		Ass./diss. local or global deficits		Aphasia	Remarks
					Melodic domain	Temporal domain	Melodic domain	Temporal domain		
R.K.	62	F	Right	A	p, i, c	r, m	Associated	Associated	–	Complete receptive amusia
I.R.	59	F	Right	A	–	–	–	–	–	
E.P.	66	F	Right	P	i, c	r, m	Associated	Associated	–	
W.J.	63	M	Right	P	p, i, c	r, m	Associated	Associated	–	
M.K.	60	M	Right	P	p, i, c	r, m	Associated	Associated	–	
G.H.	53	M	Right	P	–	–	–	–	–	
M.B.	30	M	Right	A	p	r, m	–	Associated	–	
R.F.	63	M	Right	P	–	–	–	–	–	
I.T.	69	F	Left	A	p, i, c	–	Associated	–	–	Initially anomic aphasia*
U.M.	38	F	Left	A	–	r	–	Dissociated	–	
I.F.	62	F	Left	P	p, c	r, m	Dissociated	Associated	–	
F.B.	61	M	Left	A	c	m	Dissociated	Dissociated	Anomic aphasia	
G.K.	76	M	Left	P	–	–	–	–	Anomic aphasia, dyslexia	
F.P.	69	M	Left	P	–	–	–	–	–	Initially dysarthria*
H.B.	72	M	Left	P	i, c	r, m	Associated	Associated	–	
C.F.	22	M	Left	A	–	m	–	Dissociated	Mild agrammatism	
P.R.	62	M	Left	P	p, i, c	r, m	Associated	Associated	Anomic aphasia, agrammatism	
H.L.	69	M	Left	A	c	r, m	Dissociated	Associated	–	Initially anomic aphasia*
W.H.	42	M	Left	P	–	–	–	–	Mild agrammatism	Initially Broca
G.J.	58	M	Left	A	i	r	Dissociated	Dissociated	Anomic aphasia	

Assc. = associated; diss. = dissociated; F = female; M = male; A = anterior lesion; P = posterior lesion; p = discrimination of pitch; i = discrimination of interval; c = discrimination of contour; r = discrimination of rhythm; m = discrimination of metre. * Symptoms had subsided by the time musical functions were tested.

but three had associated impairments in all subtests of higher musical functions. In all six patients suffering from left anterior lesions and in three out of six patients with left posterior lesions, receptive musical deficits of different degrees were observed. They did, however, reveal mixed patterns of associated and dissociated impairments in the melodic and/or temporal domain. Thus, a distinct type of impairment along with anterior or posterior cortical lesions did not become evident.

Attention deficits and presence of aphasia

In order to evaluate a potential interaction of attentional deficits and amusia, results in the pitch discrimination condition, i.e. in lower-level auditory information processing, were compared with the results obtained in the Alertness Test. Three patients presenting with music perception deficits did not give their consent to do the Alertness Test. Analysis of the other 17 patients did not yield any correlation: one RHD patient presented with deficits in the Alertness Test as well as a slightly diminished pitch discrimination ability. In all other cases patients presented with either pitch discrimination deficits or deficits in the Alertness Test. Also, comparison of alertness and higher musical functions showed just two patients with deficits in the Alertness Test as well as in three discrimination tasks, whereas several patients had exclusive impairments in one or other condition. In summary, a relationship between simple auditory reaction time and music perception deficits could not be verified.

At the time when musical functions were tested, six out of 12 LHD patients showed different aphasic disorders (Table 4). Just one patient (F.P.) presented with neither amusia nor symptoms of aphasia. A marked anomic aphasia was observed in patient G.K., yet without any impairment in music processing. The other five patients showing aphasic disorders plus four patients without aphasia revealed receptive musical deficits of different degree. In conclusion, there was no relationship between amusia and the presence of aphasic disorders.

Emotional musical qualities

According to the questionnaire for the assessment of the emotional musical experience, RHD patients had a less affective access to music than LHD subjects. This was reflected by a significant group effect for all affective aspects of music perception, i.e. emotional, compensating, vegetative and sentimental ($F = 7.76$, $P = 0.02$). These effects might be due to an alteration of emotional perception and affectivity following RHD. Subjectively, none of our patients reported a spontaneously altered music perception.

The patients' situation in the hospital, away from their familiar surroundings and everyday life, did not allow a definite assessment of the post-lesional musical experience. We anticipate that more subtle differentiation will be achieved when patients are questioned a second time, several months post-lesion following rehabilitation.

Discussion

In contrast to apraxia or aphasia, impairments of music perception have received considerably less clinical attention. This can be partially ascribed to the fact that the established batteries for the assessment of musical abilities are too time consuming for routine examination (Seashore, 1967). The intention of our project was to evaluate the incidence, degree and possible variants of music perception deficits following cortical lesions. To this end, we developed a standardized test battery. Evaluation of the individual emotional connotations of music was also included.

Our findings clearly support earlier reports that cortical brain lesions frequently cause impairments in music perception, presenting in various patterns and degrees (Zatorre, 1985; Samson and Zatorre, 1988; Peretz, 1990; Liégeois-Chauvel *et al.*, 1998). About two-thirds of our patients showed signs of receptive amusia. Since most subjects had little or no musical training and were musically inactive, many of these impairments would supposedly have remained unnoticed without systematic testing of receptive musical functions.

Unlike earlier studies, our patients were examined at a much earlier stage and within a very limited time frame following their cerebrovascular accidents, in order to rule out relatively short-term cerebral plasticity changes within the course of rehabilitation. This may explain why we observed more severe post-lesional impairments in music perception compared with Peretz and Liégeois-Chauvel and colleagues, who had tested several weeks or even months after the accident (Peretz, 1990; Liégeois-Chauvel *et al.*, 1998). These differences may indicate the occurrence of partially transient deficits. Therefore, retest measurements will be necessary in order to evaluate a potential improvement of receptive musical functions during the process of rehabilitation.

Deficits in neither basic musical functions, examined by discrimination of pitch, nor higher musical functions were related to basic attentional deficits as assessed by a simple reaction time test (Alertness Test). Furthermore, a relationship between the presence of aphasia and impairments in music processing could not be verified in our patients. This corresponds to findings in the literature, describing an occurrence of amusia plus aphasia as well as solitary deficits in either domain. Our findings therefore support the hypothesis that musical stimuli are predominantly processed independently from language functions, even though there may be a coexistence of language and musical impairments (Sergent *et al.*, 1992; Basso, 1993; Hodges, 1996).

Unexpectedly, anterior and posterior lesions did not show different patterns of impairment in music processing. This supports the supposition of inter- and intra-individual variation in neural networks underlying music processing rather than homogeneously localized systems.

Are local and global structures processed by hemisphere specific networks?

RHD patients revealed the overall phenomenon that discrimination of global stimuli poses more difficulties than discrimination of local structures. In LHD patients this effect was also seen very clearly in the temporal dimension and as a tendency in the melodic conditions. These findings are certainly surprising as they partially contradict the initially outlined supposition on hemispheric specificity for musical information processing, which assumes a left-hemisphere advantage in the processing of local stimuli and a right-hemisphere advantage for global stimuli. The fact that our left-hemisphere patients had problems not only in local stimulus processing but showed similar, significant impairments in the discrimination of contour, and even more severe impairments in the discrimination of metre is not consistent with previous findings of Peretz and Liégeois-Chauvel and colleagues: their LHD patients showed isolated deficits in the discrimination of interval along with intact contour-processing mechanisms (Peretz, 1990; Liégeois-Chauvel *et al.*, 1998). In contrast, patients in our LHD group showed all possible variations of isolated and/or associated local or global deficits, with no difference between anterior or posterior lesion sites.

These discrepancies may be explained by new concepts of cognitive processing, postulating an enlarged role of left-hemispheric networks. According to Robertson and Lamb, a bilateral parietal processor is necessary for controlling the distribution of attentional resources to global and local levels in the visual domain. Furthermore, bilateral temporotemporal pathways are used to communicate between global and local subsystems and to fine-tune them (Robertson and Lamb, 1991). Thus, it may be speculated that an involvement of these networks contributes to the scattered patterns observed in our study. Clearly, a large patient group with a wide range of well-classified lesions will be necessary to clarify the role of left-hemispheric parietal or temporal networks by a more fine-grained analysis of the relationship between structural damage and functional loss. Another aspect not taken into account in previous studies is cerebral plasticity: the loss of global processing abilities along with intact local information processing that we observed in several LHD patients may be explained by compensating mechanisms reactivating a local processor in the right hemisphere. Recently it has been demonstrated that such compensatory mechanisms with recruitment of contralateral brain regions play an important role in the auditory system (Engelien *et al.*, 1995; Thomas *et al.*, 1997).

Is music perception based on a hierarchical system?

Our results in both groups of brain-damaged patients lead to a reflection on the hypothesis of a hierarchical system in music perception: the assumption of a right-hemisphere global system embedding local information processing can be supported by the findings in our RHD group, not only in the melodic but also in the temporal dimension (Dowling, 1982; Peretz, 1990). All patients presenting with signs of amusia following RHD showed associated impairments in global and local conditions. Similar findings for the discrimination of interval and contour following RHD, but not for the temporal dimension, have been described by Peretz and Liégeois-Chauvel and colleagues (Peretz, 1990; Liégeois-Chauvel, 1998). Unlike the LHD group, none of our RHD patients presented with deficits in global processing without signs of local processing impairment and none had an exclusive deficit in local processing conditions. This suggests a two-stage process, with the necessity of an initial right-hemisphere recognition of global structures followed by identification of local stimuli via left-hemisphere subsystems that are unable to function autonomously.

The right hemisphere, however, appears to be independent from left-hemisphere functioning since global processing was undisturbed in the presence of severe local perceptual impairments following LHD. As outlined earlier, it may even compensate for damage to left-hemisphere areas in individual cases.

Are melodic and temporal structures processed by autonomous neural networks?

The question of associated or separate neural networks processing melodic and temporal information is still controversial, due to contradictory findings in brain-damaged patients (Peretz, 1990). Ten out of 14 symptomatic subjects in our study demonstrated combined deficits in melodic and temporal perception in local and/or global conditions. This indicates a predominance of associated neural substrates underlying melodic and temporal music perception. However, similar to other authors, we also saw three patients who presented with dissociated deficits in either melodic or temporal discrimination tasks (Brust, 1980; Mavlov, 1980; Peretz, 1990). This again points at a perceptual independence of melody and rhythm, and it seems reasonable to assume that they are processed by separate neural subsystems which may be closely linked or partially integrated.

The musical experience

None of our patients complained about an alteration of the emotional musical experience. This subtype of receptive amusia is very rare (Mazzucchi *et al*., 1982; Mazzoni *et al*., 1993) but it is certainly easily missed when evaluated during a patient's stay in the hospital. A better impression of the incidence of anhedonic amusia might be gained in follow-up examinations.

Evaluation of the questionnaire on 'Musikerleben' revealed a significant group effect of a less affective appreciation of music in RHD patients. This underlines earlier findings showing a right-hemisphere advantage for the identification of the affective tone of dichotically-presented musical sequences and for emotional displays (Bryden *et al.*, 1982; Joseph, 1988). An altered processing of emotional information has also been described in patients suffering from right-hemisphere lesions (Heilman *et al*., 1978; Borod, 1992); however, due to the small number of patients in the RHD group and the acute state of illness at the time of testing, a definite interpretation of the potentially altered emotional perception is premature.

Conclusion

In conclusion, the diverse patterns of perceptual musical impairments in our brain-damaged patients, taken together with the variable literature findings on receptive amusia, still do not allow an adequate outline of the neural substrates underlying music perception. The miscellaneous manifestations of post-lesional perceptual deficits give rise to the supposition that musical information processing may, to a considerable degree, be based on highly individual networks. This assumption is supported by single cases with unusual specific patterns of deficits; e.g. one patient who was very interested in classical music but had little musical training (category F) had suffered a right-parietal infarction and showed an exclusive deficit in the discrimination of pitch, whereas both discrimination of interval as well as of contour, plus the Alertness Test, were found to be undisturbed. It might be possible that this patient used different processing strategies in the basic task than in the complex tasks. The theory of individually developed neural substrates may become more plausible when it is realized that the perception of musical structures is an ontogenetically and phylogenetically late acquired ability. In addition, musical expressive and perceptual experience are extremely non-uniform features within society; they may be affected by the individual environment and be interrelated with personality characteristics and other individual cognitive abilities (Tighe, 1993). We have to consider that music perception is not exclusively based on specific music processing substrates: in the stage of music perception, diverse generic cognitive functions are also likely to be used in varying degrees, e.g. attention, working memory, phonological loop and frontal functions.

In summary, we conclude that perceptual musical functions do not show a clear hemispheric lateralization and that the neural substrates underlying local and global musical information processing present a cross-hemisphere heterogeneous and fragmented system. Corresponding to the complexity of musical information itself, we therefore suggest that music processing is based on widely distributed neural networks modulated by individual aspects of musicality and music experience.

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