Functional dissociations following bilateral lesions of auditory cortex
Isabelle Peretz; Regine Kolinsky; Mark Tramo; Raymonde Labrecque; et al
Brain; Dec 1994; 117, 6; ProQuest Psychology Journals
pg. 1283

Brain (1994), **117**, 1283–1301

Functional dissociations following bilateral lesions of auditory cortex

Isabelle Peretz,[1,2] Régine Kolinsky,[3] Mark Tramo,[5] Raymonde Labrecque,[2] Claude Hublet,[4] Guy Demeurisse[4] and Sylvie Belleville[1,2]

[1]*Département de Psychologie, Université de Montréal,* [2]*Centre de Recherche du Centre Hospitalier, Côte-des-Neiges, Université de Montréal, Montréal, Canada,* [3]*Laboratoire de Psychologie Expérimentale, Université Libre de Bruxelles,* [4]*Service de Revalidation Neurologique, Hôpital Universitaire Brugmann, Bruxelles, Belgium and* [5]*Department of Neurobiology, Harvard Medical School and Neurology Service, Massachusetts General Hospital, Boston, USA*

Correspondence to: Isabelle Peretz, Département de Psychologie, Université de Montréal, CP 6128, succ. Centre-ville, Montréal (Québec), Canada H3C 3J7

Summary
We present two patients with bilateral lesions of the superior temporal cortex who manifested a number of functional dissociations in the auditory domain. The perception of speech and environmental sounds were preserved; yet, the perception of tunes, prosody and voice was impaired. As the processing of melodic but not rhythmic variations in musical sequences was selectively disturbed, the deficit cannot be attributed to a general impairment in auditory memory or sequential processing. These findings suggest that melody processing is not mediated by a general-purpose auditory architecture but by specialized cortical subsystems residing within the lesioned areas. Current taxonomies of auditory agnosia and models of normal music cognition are evaluated in light of the functional dissociations manifested by these patients.

Key words: auditory agnosia; amusia; auditory cortex; voice; prosody

Introduction
Auditory agnosia was originally defined by Freud (1891) as a selective disorder of sound recognition. Owing to an almost constant association of bilateral cortex lesions, it is a rare syndrome that is characterized by a relative preservation of elementary psycho-acoustic functions and sparing of the ability to recognize the events via other sensory modalities. Despite this long history, delineation of the functional dissociations occurring within the broad scope of the clinical syndrome remains incomplete. For example, the term auditory agnosia has been used to describe two different clinical presentations. In the broader sense, it is employed when the patient is unable to interpret all types of sounds; in the more restrictive sense, it refers to deficits confined to the recognition of non-verbal sounds. The viability of this distinction is still a matter of dispute. Indeed, most cases reported in the literature correspond to the broader designation; i.e. the impairments cut across auditory domains (for a recent review, *see* Lechevalier *et al.*, 1984). This observation has led some authors to argue that auditory agnosia is the result of an insult to a unitary mechanism of sound recognition that mediates fine auditory resolution or temporal sequencing of sounds (Albert and Bear, 1974; Auerbach *et al.*, 1982; Buchman *et al.*, 1986; Tanaka *et al.*, 1987; Mendez and Geehan, 1988; Buchtel and Stewart, 1989).

Explaining all the elements of auditory agnosia in terms of a disruption of a single temporal mechanism is an over-simplification. The wide range of deficits encompassed by the syndrome comprises a heterogeneous category within which functional subdivisions exist. One such line of fractionation is domain-specific. Among the three domains traditionally investigated (i.e. speech, music and environmental sounds), cases of selective disruption have been reported. This heterogeneity in the nature of auditory agnosia is the major focus of the present paper. Delineating the domains of auditory agnosia provides a rich source of information regarding the functional architecture that underlies auditory cognition. Moreover, the study of dissociations between the different forms of agnosia may provide important clues towards a clarification of both the taxonomy of auditory disorders and their underlying neural substrates.

© *Oxford University Press 1994*

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Case reports

The two cases that are reported here had an analogous history of successive cortical damage, first in the right hemisphere and then in the left hemisphere, following rupture and surgical repair of the middle cerebral artery on each side. Both patients are right-handed, well-educated non-musicians. One is a young woman living in Brussels (Case C.N.), and the other is an older man living in Montreal (Case G.L.). Therefore, these two cases were investigated by independent teams with the exception of the first author who tested both cases. Despite this geographical distance, the two cases are strikingly similar and thus compel their joint description in the present paper.

Case C.N.

Neurological history

The first case, C.N., is a 35-year-old nurse. She was admitted to the hospital in December 1986, when she suffered the sudden onset of severe headache and neck pain; CT of the head was normal, but a lumbar puncture yielded bloody cerebrospinal fluid. Cerebral angiography revealed an aneurysm of the right middle cerebral artery. On the fifth day in hospital, the aneurysm was clipped. Post-operatively, she had a mild left hemiparesis. In February 1987, successful repair of the right middle cerebral artery aneurysm was confirmed angiographically, but a new mirror aneurysm of the left middle cerebral artery was discovered. Two weeks later, the left middle cerebral artery aneurysm was clipped. Postoperatively, C.N. suffered transient word-finding difficulty and persistent anosmia; in addition, she complained that her perception of music was deranged. Two weeks later, normal pure tone detection thresholds and normal speech discrimination thresholds were documented using standard audiometric methods. C.N.'s performance on the French version of the Boston Diagnostic Aphasia Examination (BDAE) (Goodglass and Kaplan, 1972) showed a perfect score on the word discrimination subtest and an overall score of 114 out of 119 on auditory comprehension tasks (Table 1); in total, the BDAE showed no evidence of aphasia. On the Wechsler adult intelligence scale, the full-scale IQ was 98, verbal IQ 103, performance IQ 94, and on the Wechsler memory scale, her memory quotient was 103.

Over the course of the year following her second craniotomy, C.N. suffered major depressive episodes. Following one of these, in March 1988, she was again admitted to the hospital for further neuropsychological evaluation and psychological support. A CT scan revealed bilateral peri-Sylvian infarcts (*see below*). Because of persistent complaints of impaired music perception, she was referred to our laboratory.

When we first examined C.N. in March 1988, she complained exclusively about her music-related symptoms. She stated that she was no longer able to recognize familiar tunes or sing them. She complained that singers sounded like they were talking instead of singing. However, she was still able to dance to music. She admitted to difficulty identifying voices over the telephone but denied problems recognizing environmental sounds. She was again administered the French version of the BDAE; as before, auditory comprehension was perfect and there was no evidence of aphasia. In fact, C.N. achieved the maximum possible score on all subtests except animal naming (23 out of 25) and singing (one out of two). On a dichotic test of consonant–vowel syllable recognition, C.N. performed normally: she correctly repeated 70% of left ear stimuli when she attended to the left ear and 73% of right ear stimuli when she attended to the right ear. In comparison, the mean and range for 12 age-matched normals were 65% (range: 40–100) for the left ear, and 75% (range: 57–100) for the right ear. The full-scale IQ was 97, verbal IQ 99, performance IQ 95 and memory quotient 115. On Warrington's recognition memory test, she scored 42 out of 50 for words and 45 out of 50 for faces, with both scores falling within normal limits.

C.N. received 15 years of education but had no formal training in music. As her father was a 'cellist who played regularly at home and who directed amateur bands at weekends, she was raised in a musical environment. Prior to her illness, C.N. was an avid listener to music and sang everyday to her child. She meets criteria for Grison's (1972) third level of musical culture. She is fully right-handed, as assessed by Oldfield's questionnaire (1969).

Lesion localization

Figure 1 illustrates CT scans obtained in March 1988, ~1 year after C.N.'s second craniotomy. The atlases of Matsui and Hirano (1978), Talairach and Tournoux (1988) and Damasio and Damasio (1989) were used to estimate lesion localization. The distribution and density of the lesions within each hemisphere are consistent with ischaemic infarction involving the territories of the anterior branches of the inferior division of the middle cerebral artery. The rostral half of the superior temporal gyrus in each hemisphere is damaged, but the transverse gyrus of Heschl and caudal superior temporal gyrus appear to be intact. There is extension of the lesions into both temporal poles, both middle temporal gyri, the right insula and, to a limited extent, the right inferior frontal gyrus. Thus, the preservation of C.N.'s speech and language functions is likely attributable to preservation of the left primary auditory area and putative language area of Wernicke.

In light of previous cytoarchitectonic (Galaburda and Sanides, 1980) and electrophysiological (Celesia, 1976; Liegeois-Chauvel *et al.*, 1991) data, these CT findings indicate that C.N. sustained bilateral lesions of rostral auditory association cortex with sparing of the primary and caudal association areas. Although there are no lesions of the medial temporal cortex or lateral prefrontal cortex, these are likely disconnected from all or most of their auditory cortical input, which arises from the rostral association areas in anthropoids (for review, *see* Pandya and Yeterian, 1985); similarly, reciprocal projections from these supramodal structures to auditory cortex are likely interrupted.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 1 *C.N.'s results [just after onset (in 1987) and a year later] on the BDAE and G.L.'s results (in 1990) on BDAE and Montréal–Toulouse 86β subtests*

	C.N.			G.L.	
	1987	1988	Maximum possible score	1990	Maximum possible score (or cut-off score)
Token test	—	—	—	32	36
Boston Diagnostic Aphasia Examination					
Fluency					
Articulation rating	7	7	7	7	7
Phrase length	7	7	7	4	7
Verbal agility	14	14	14	—	—
Auditory comprehension					
Word discrimination	72	72	72	47	(40)
Body part identification	20	20	20	—	—
Commands	12	15	15	7	8
Complex material	10	12	12	—	—
Naming					
Responsive naming	30	30	30	—	—
Confrontation	105	105	105	31	(25)
Animals	25	23	25	25	(15)
Body parts	30	30	30	—	—
Oral reading					
Words	30	30	30	30	(26)
Sentences	10	10	10	3	3
Repetition					
Words	10	10	10	29	(24)
High probability phrases	8	8	8	8	8
Low probability phrases	8	8	8	6	8
Paraphasia					
Neologisms	0	0	—	—	—
Verbal	0	0	—	—	—
Literal	0	0	—	—	—
Automated speech					
Automatized sequences	8	8	8	—	—
Reciting	2	2	2	—	—
Reading comprehension					
Symbol comprehension	10	10	10	—	—
Word recognition	8	8	8	—	—
Comprehension of oral spelling	7	8	8	—	—
Word picture matching	10	10	10	—	—
Reading sentences, paragraphs	10	10	10	10	(13)
Writing					
Mechanics	3	3	3	—	—
Serial writing	47	47	47	—	—
Primer dictation	15	15	15	—	—
Written confrontation naming	10	10	10	—	—
Spelling to dictation	10	10	10	—	—
Sentences to dictation	12	12	12	—	—
Narrative writing	4	4	4	—	—
Singing					
Melody	0	1	2	—	—
Rhythm	2	2	2	—	—

Case G.L.

Neurological history

G.L. is a 61-year-old business man who suffered an aneurysmal subarachnoid haemorrhage in December 1979, that presented with sudden loss of consciousness. On admission to the hospital, he was drowsy and had nuchal rigidity (Bottrel grade I); head CT revealed blood in the occipital horns of the lateral ventricles. Cerebral angiography disclosed bilateral aneurysms of the trifurcation of the middle cerebral arteries, a right posterior communicating artery

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

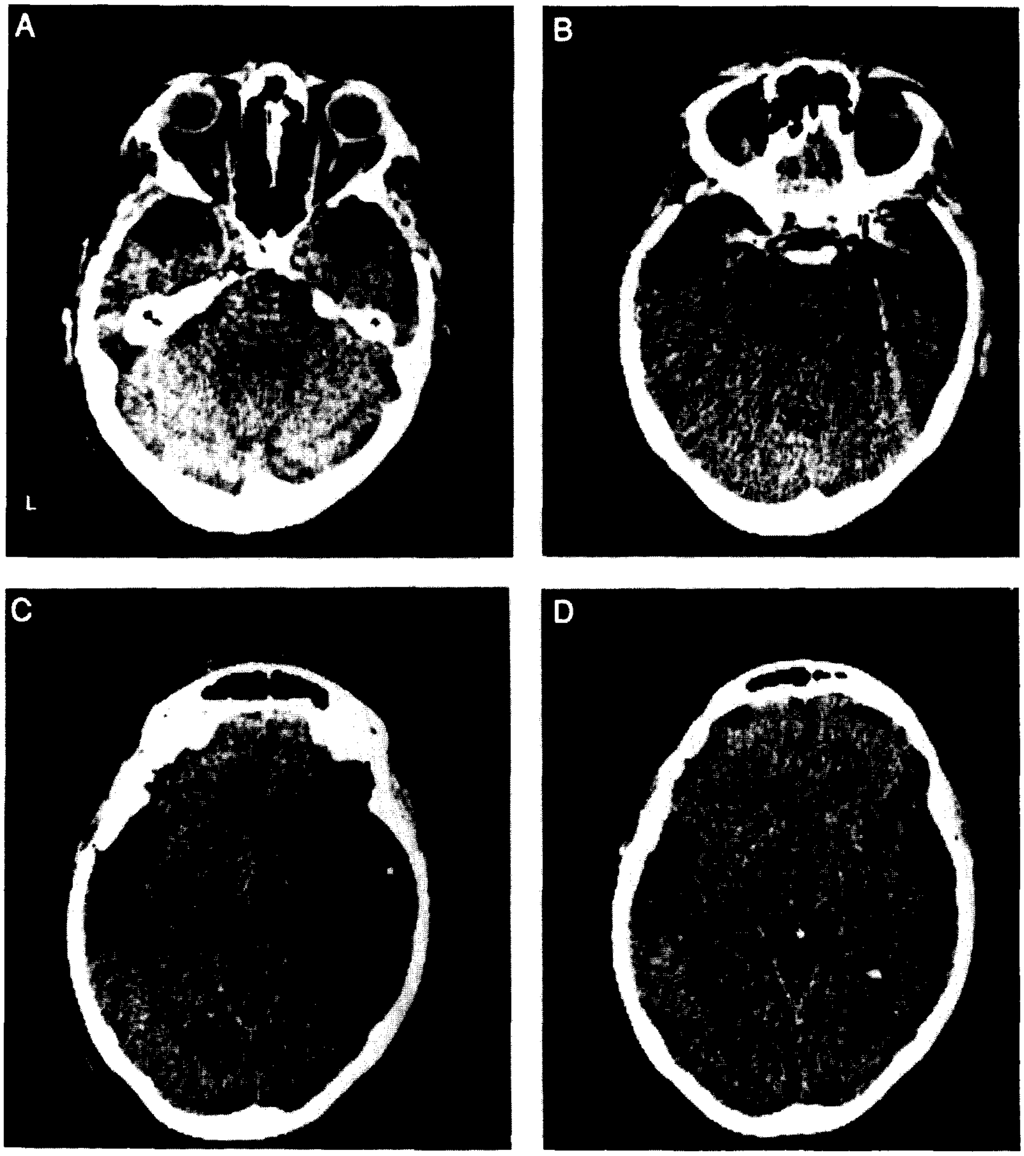

Fig. 1 Case C.N. Contiguous, 8 mm thick, horizontal CT sections obtained without intravenous contrast in March 1988, ~1 year after C.N.'s second craniotomy. Hypodensities are seen in the superior temporal gyri (**B–D**), middle temporal gyri (**B–D**) and temporal poles (**A–B**) of both hemispheres, and in the insula (**C–D**) and inferior frontal gyrus (**C–D**) of the right hemisphere. Additional hypodensities in both temporal poles appear in the section inferior to **A** (not shown). Aneurysm clip artefacts are seen in **B**.

(PCoA) aneurysm, and spasm involving the carotid siphon, middle cerebral artery and anterior cerebral artery. The right middle cerebral artery aneurysm was clipped in January 1980. A few months later, he returned to work without neurological residua. In September 1980, G.L. complained of persistent headache. An electroencephalogram revealed right frontotemporal slowing. In February 1981, angiography documented successful repair of the right middle cerebral artery aneurysm. In April 1981, the left middle cerebral artery aneurysm was clipped. Intra-operatively, a vessel adherent to the aneurysmal pouch was sacrificed under microscopic dissection. Postoperatively, G.L. manifested impaired speech and music perception, impaired reading comprehension and fluent, paraphasic speech. There were no associated visual, motor, or somatosensory deficits. Serial head CT scans revealed bilateral peri-Sylvian infarcts, and single photon emission computed tomography performed with Technetium 99m-labelled hexamethyl-propyleneamine oxime showed bilateral peri-Sylvian hypoperfusion. In October 1981 G.L.'s language disorder was classified as Wernicke's aphasia following his scores on the Token test and on subtests from the BDAE. The verbal IQ was 91, performance IQ 114 and memory quotient 86. G.L. subsequently received 2 years of speech therapy and recovered

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

most of his speech and language abilities. At the time of the present experiments, he was independent in all activities of daily life.

In August 1989, G.L. was referred to our laboratory because of persistent complaints concerning music perception. He stated that he was unable to recognize familiar music and that he no longer enjoyed listening to music. However, he was still able to dance to music. G.L. reported difficulty with speech perception under conditions of competing sounds or rapid speech. He also complained of word-finding difficulties. The full-scale IQ was 120, verbal IQ 111, performance IQ 122 and memory quotient 107. In October 1990, we administered the Token test (DeRenzi and Faglioni, 1978), several BDAE subtests and several subtests of the Montréal–Toulouse 86β (Béland and Lecours, 1990; table 1); no residual deficits in speech and language functions could be documented. On the dichotic fused rhymes test (Wexler and Halwes, 1983), G.L.'s overall score was 94.1%; in comparison, the mean of 12 age-matched normals was 96.2% and their range 94.1–100%. However, G.L. reported 46 of right ear stimuli and 65 of left ear stimuli (after the dominant items had been subtracted), whereas the normal controls showed, on an average, a right ear advantage (mean and range: 68.9, 46–92 for right ear stimuli; 46.5, 29–68 for left ear stimuli). Yet, four out of the 12 aged-matched controls also exhibited a left-ear advantage. Praxis, calculations and visual functions were normal. Pure tone audiometry revealed mild elevation in detection thresholds at high frequencies in both ears, consistent with age-related sensorineural hearing loss (I. Peretz, C. Paquette and A. R. Lelours, unpublished results).

G.L. received 14 years of education (including 2 years as an undergraduate student in pharmacology) and had no formal training in music. Prior to his illness, G.L. was an avid listener of popular and classical music and attended concerts regularly. He meets criteria for Grison's (1972) third level of musical culture.

Lesion localization

Figure 2 illustrates CT scans obtained in July 1990, ~9 years after G.L.'s second craniotomy. The distribution and density of the lesions within each hemisphere are consistent with ischaemic infarction in the territory of the middle cerebral artery; the large left hemisphere infarct involves most of the territory of the inferior division. There is extensive damage to the left superior temporal region involving the superior temporal gyrus, transverse gyrus of Heschl, temporal pole and insula; part of the caudal third of the superior temporal gyrus and perhaps some of the transverse gyrus appear to be spared. In addition, there is a hypodensity in the region of the left inferior frontal gyrus that may represent infarction or widening of the Sylvian fissure secondary to surrounding tissue loss. The smaller right hemisphere lesion involves the rostral superior temporal gyrus, temporal pole, insula and inferior frontal gyrus.

These CT findings indicate that G.L. sustained extensive damage to the left auditory cortex, including all of the rostral association areas, all or much of the primary area and much of the caudal association areas. In the right hemisphere, the lesion involves part of the rostral association cortex. Thus, likely interrupted are all of the long connections of the rostral left auditory cortex, some of the long connections of the rostral right auditory cortex and some of the long connections of the caudal left auditory cortex. The latter project to and from dorsolateral frontal, lateral temporal, and posterior cingulate cortex in anthropoids.

Experimental methods and results

Control subjects

Five female subjects with no history of neurological or psychiatric disease served as controls for the experiments carried out with C.N.; they were all the same age, and had the same musical background and education (most of them were also nurses working in hospitals) as C.N.

Five male subjects with no history of neurological or psychiatric disease who were aged between 59 and 66 years, had between 13 and 17 years of education and had no formal training in music, served as controls for the experiments carried out with G.L. For Experiment 2, G.L.'s performance was compared with that of five age-matched and education-matched males studied previously (Peretz, 1990; age: 49–76 years, education: 13–17 years).

The two patients and all control subects gave informed consent to all tests administered.

General procedure

All stimuli were recorded onto tape and presented in free field at a loudness level that was comfortable and customary for the listener.

Experiment 1: recall and recognition of familiar melodies

Material and procedures

We presented musical excerpts to C.N. and G.L. that were once highly familiar to them and contrasted these with unknown ones. Familiar melodies consisted of (i) excerpts from commercial recordings (Peretz, 1990); (ii) excerpts from commercial recordings selected from the patient's own music collection; (iii) well-known nursery tunes; (iv) excerpts from well-known folk-songs and instrumental pieces that were played one note at a time via a synthesizer controlled by a computer (Peretz *et al.*, 1994). C.N. was administered the first four types of materials and G.L. was administered the fourth type. Unfamiliar sequences consisted of (i) excerpts that were matched to the nursery tunes in terms of length and genre, for they were taken from the same repertoire (Berthier, 1979), and (ii) excerpts of a subset of the afore-

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

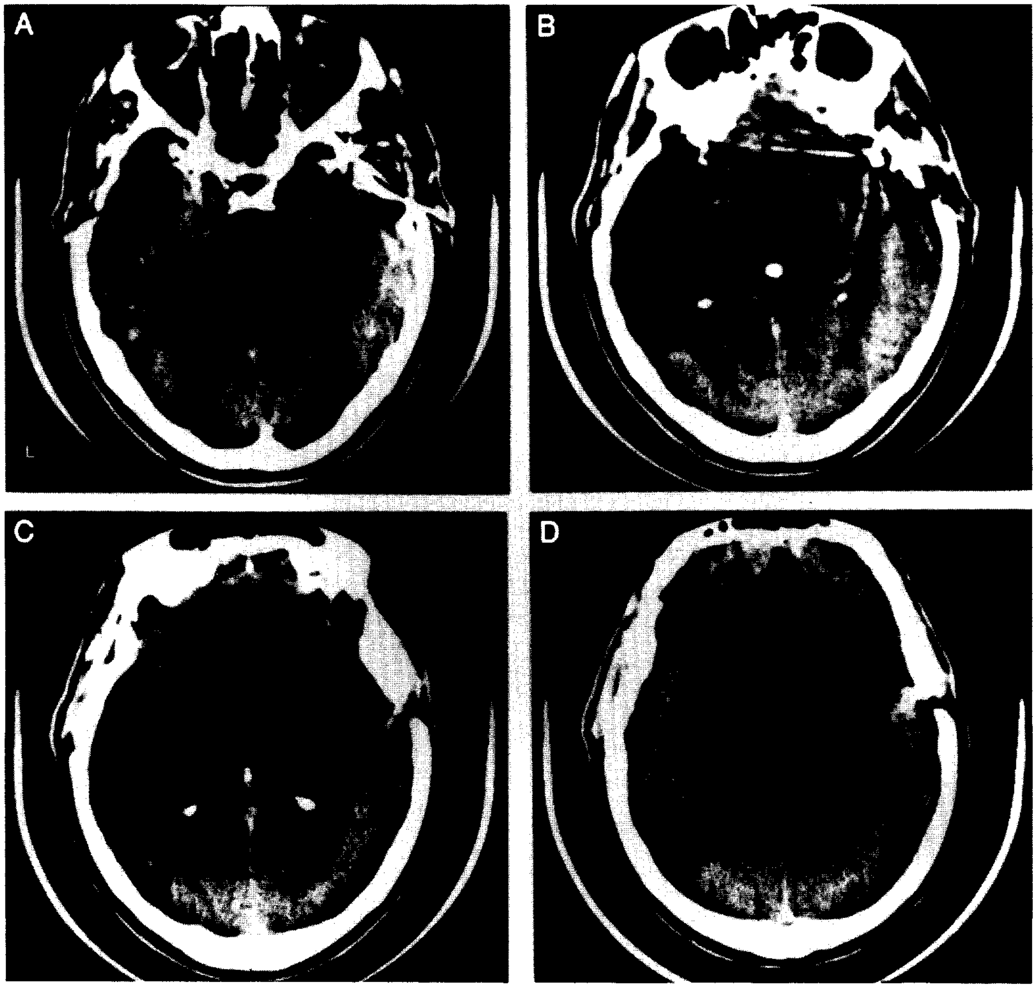

Fig. 2 Case G.L. Contiguous, 10 mm thick, horizontal CT sections obtained without intravenous contrast in July 1990, ~9 years after G.L.'s second craniotomy. Hypodensities are seen in the superior temporal gyri (**B–D**), temporal poles (**B–D**), inferior frontal gyri (**D**) and insulae (**B–D**) of both hemispheres, and in the transverse gyrus of Heschl (**C–D**), inferior parietal lobule (**D**) and middle temporal gyrus (**B–C**) of the left hemisphere. Additional hypodensities in the left inferior parietal lobule appear in the section superior to **D** (not shown). Aneurysm clip artefacts are seen in **A** and **B**.

mentioned well-known folk-songs that were played in reverse. C.N. was administered the first type and G.L. the second type.

Several different response modes were used: (i) naming; (ii) multiple-alternative forced-choice recognition; (iii) 'same–different' classification; (iv) 'familiar–unfamiliar' decision. The particular response paradigm used for a given task is explained in the presentation of the results. No limits were imposed on response time.

Results

In March 1988 C.N. was able to name only one out of 12 melodies taken from her personal record collection. She was able to name only two out of 10 familiar melodies selected from commercial recordings. She was able to correctly classify only 11 out of 20 nursery tunes as familiar versus unfamiliar, judging all but one as unfamiliar. She was able to discriminate correctly pairs of familiar nursery tunes as the same or different in 20 out of 30 trials; thus, she was not even very good at discriminating them one from another. In December 1989 C.N. was able to name only five out of 80 well-known musical excerpts: she thought an additional 23 of the 80 sounded familiar but was unable to name them. This occurred more often for musical material taken from songs (17 cases) than for instrumental material (five cases). When prompted with the corresponding titles presented in isolation, C.N. scored 61 out of 80. For some of them, the associations were vivid and accurate. For example, when cued with the title 'The four seasons', she immediately retrieved 'Vivaldi' as the composer's name and evoked a specific memory associated with this music (e.g. she recalled that the first time that she had heard that music was 15 years ago when working with a surgeon who usually listened to 'The four seasons' during surgery). In May 1990 C.N. was

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

presented with 12 well-known nursery tunes and 12 unknown nursery tunes hummed on 'la, la, la . . .' by a female singer; she correctly classified 15 out of 24 melodies as familiar or unfamiliar when the first line of the tune was presented and 13 out of 24 when the second line of the tune was presented (*see* Table 2). Thus, C.N. performed at chance (both $P > 0.10$, by two-tailed binomial tests). In contrast, normal controls correctly classified 19 out of 24 when the first line was presented and 18 out of 24 when the second line was presented.

G.L. was unable to name any of 140 well-known musical exerpts (including the Canadian national anthem) that are familiar to any French-Quebec listener (Peretz *et al.*, 1994). After hearing 19 of these excerpts, he stated: 'I think I knew that tune before.' He correctly classified 50 out of 74 such musical excerpts as familiar versus unfamiliar. While performance on the latter task was significantly better than chance ($Z = 2.7$, $P < 0.01$ by a binomial test), it was well below the range of normal controls (63–69 out of 74).

Experiment 2: lyric recognition

Material and procedures

We presented lyrics to C.N. and G.L. that were either familiar or unfamiliar. In some cases, the lyrics corresponded to the tunes used in Experiment 1. (Tune refers here to musical sequences without lyrics. The choice of 'tune' instead of 'melody' is motivated by the need to restrict the latter term to pitch variations in musical sequences as distinct from the 'rhythm', describing the temporal variations. Tune refers thus to sequences where both melody and rhythm are varying.) For a subset, care was taken to control for the lyrics' location in the songs, as the first line of lyrics often includes the song title. Thus, first lines as well as second lines were employed. These were either lyrics of unknown songs taken from the same repertoire or familiar proverbs (e.g. 'loin des yeux, loin du coeur'—out of sight, out of mind). Subjects were required to decide whether or not the lyrics were taken from a well-known song.

Results

In March 1988, when presented with 60 written lyrical segments, C.N. correctly classified 58 as familiar or unfamiliar. When presented with 60 spoken lyrical segments, she correctly classified 51 as familiar or unfamiliar. Controls achieved on average 57. C.N. did as well when judging second lines as familiar or unfamiliar, with 28 out of 32; controls obtained an average of 27.4. Similarly, she easily discriminated lyrics from proverbs in 18 out of 20 items (controls also obtaining an average of 18). In May 1990, C.N. correctly classified as familiar or unfamiliar 23 out of 24 first lines and 19 out of 24 second lines of the lyrics belonging to the nursery tunes tested previously in hummed version; her score was well within the range of normal controls (Table 2).

Table 2 *Percentage of correct responses obtained by C.N. (in 1990) on various familiarity judgement tests involving either the tune or the lyrics of the same songs*

Hummed tune		Spoken lyrics	
First line	Second line	First line	Second line
62.5 (77.1)	54.2 (74.2)	95.8 (95.0)	79.2 (82.5)

Mean control scores are presented in parentheses.

G.L. correctly classified 16 out of 20 lyrical segments as familiar or unfamiliar. While this score is significantly better than chance ($P < 0.02$), it is below the range of normals (19–20 out of 20). G.L. also correctly distinguished well-known lyrics from proverbs in 16 out of 20 trials, which is within the range of the normals' performances (14–17). Since the lyrics were mostly taken from nursery tunes rather than folk-songs, G.L. stated that none were familiar to him before his illness. Because of his penchant for contemporary music and, in particular, Jacques Brel, we presented the lyrics of 24 songs written by Brel, half of which Brel had not recorded (but published) (Brel, 1982). G.L. correctly discriminated recorded from unrecorded lyrics in 18 of 24 trials, within the range of normal controls (15–19).

Thus, for both patients, and particularly C.N., it appears that the processing of familiar song lyrics was preserved relative to processing of the tunes.

Experiment 3: discrimination and recognition of unfamiliar tunes

Material and procedures

C.N. and G.L. were tested with a battery of seven sub-tests described in detail elsewhere (Peretz, 1990). This battery assesses the discrimination of various aspects of music that are known to contribute to music processing, while keeping the material as natural and identical as possible across conditions. The material was generated from a pool of 24 novel musical sequences that respected the tonal structure of the Western idiom and were played one note at a time on a piano. The tests assess abilities to discriminate isolated musical pitches, to detect variations in musical sequences due to pitch changes, to detect variations in musical sequences due to rhythmic changes and finally to recognize musical sequences heard in prior tests in the battery.

Results

The results are summarized in Table 3. Compared with normal controls, both C.N. and G.L. showed impaired discrimination when the standard and comparison melodies differed with respect to pitch variations but not when they differed with respect to timing. In contrast, both patients performed within the range of normal controls when asked to judge the relative

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 3 *Percentages of correct responses obtained on the musical battery (Peretz, 1990) by C.N. at the time of testing (March 1988) and after some recovery (December 1989), as well as the means of five normal controls matched to C.N. socio-demographic variables, and the data of G.L. as well as those of his matched-controls, with their lowest and highest scores in parentheses*

	C.N.			G.L.	
	1988	1989	C.N.'s controls	1990	G.L.'s controls
Isolated pitches	87.5	100.0	94.2 (79.2–100)	83.3	95.8 (91.7–100)
Melodic variations	33.3	51.4	72.5 (63.9–83.3)	56.3	89.6 (76.7–99.0)
Rhythmic variations	83.9	88.2	89.2 (76.0–98.1)	88.2	96.4 (90.1–100)
Delayed recognition	44.4	61.1	81.7 (77.8–88.9)	33.3	86.7 (72.2–94.4)

pitch of two single tones. Thus, G.L. and C.N. showed a similar pattern of performance in the discrimination tests; however, G.L. was far worse than C.N. with respect to delayed recognition. Despite the fact that C.N. showed slight apparent improvements in pitch discrimination, melody discrimination and delayed recognition between 12 and 21 months post-onset, she maintained a dissociation between the processing of melodic variations, which was impaired, and the processing of temporal variations, which was relatively spared. Further experimental work has confirmed that this dissociation is very robust (Peretz and Kolinsky, 1993). With respect to G.L.'s impairment in processing pitch variations, it was found that he systematically failed to use scale information, whereas he was able to use pitch contour and intervallic distance as cues for melody discrimination. This particular pattern of dissociation, termed auditory atonalia, has been the subject of detailed investigation (Peretz, 1993*a*).

Experiment 4: recognition of environmental sounds and musical instruments

Material and procedures

The category of environmental sounds is ill-defined. Traditionally, it covers very diverse sound sources. Moreover, these sources are usually tested with a very limited number of exemplars. We attempted here to be a little more systematic in covering different categories, each containing many exemplars: there were 12 animal cries, seven transportation noises, seven human noises and 19 indoor noises (including eight ringing sounds). Musical instruments were assessed separately in different sub-tests: (i) single instrumental pieces taken from commercial recordings; (ii) synthesized approximations of natural instruments (piano, banjo, flute and bell) playing a novel tune; (iii) synthesized approximation within either a string instrument class (piano, sitar and harpsichord) or a wind instrument class (trumpet, horn and brass). C.N was tested with all three tests, while G.L. was only tested with the first one, but with a larger selection than C.N. The response mode was: (i) naming, (ii) multiple-choice picture-matching or (iii) 'same–different' classification.

Results

In May 1988 C.N. correctly named 38 out of the 45 environmental sounds (84.4%); she recognized six of the seven missed items among four line-drawings of possible sound sources from the same category. Thus, her overall recognition score for environmental sounds was 44 out of 45 (97.7%). Control subjects named between 29 and 40 of the sound samples, with a mean of 36.8 out of 45 (81.8%); normal performance when recognition score is added was on average 42 out of 45 (93.3%). Contrasting with her excellent performance for environmental sounds, C.N. correctly named only two out of six musical instruments (piano and drums) when taken from commercial recordings, and failed to identify the 'cello, her father's musical instrument. This impairment applied as well to the naming of the synthesized approximations; she correctly named only one out of eight. In contrast, controls correctly named between five and seven. Knowledge of all these instruments was verified by asking her to point to the picture corresponding to the named instrument by the examiner; she made no error. Finally, C.N. had no difficulty discriminating these musical instruments. She scored 92%. She did as well when discriminating instruments falling into the same acoustic category, obtaining 24 out of 24. Thus, C.N.'s impaired recognition of musical instruments cannot be attributed to disturbed perceptual abilities.

G.L. had no difficulty in naming 42 of the 45 environmental sounds (93.3%). On 16 of the 20 trials, G.L. correctly identified which of 12 possible instruments had produced the excerpt. However, only two of these responses corresponded to the correct name (guitar and violin), the remaining 14 correct identifications were provided by gesture. His errors (guitar mistaken for a harp, jew's-harp with mouth organ) were within the appropriate acoustic category (e.g. plucked strings). Furthermore, when one of the missed items (guitar) played a second, different excerpt, it was correctly named. In contrast, controls correctly named the instrument in 18–20 of the 20 excerpts. While the difference between G.L. and normals is not large, it raises the possibility of a slight impairment in musical instrument recognition. Still, G.L. did perform well above chance.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Experiment 5: prosody recognition

Material and procedures

Prosody concerns the medium of communication, or how the message is realized in the speaker's verbalizations; it results from variations in voice quality, pitch, rhythm and stress. These variations are essential for conveying emotional information and also contribute to speech intelligibility at several levels of organization of the speech stream. We will refer to the assessment of the former and of the latter as 'emotional tone' tests and 'linguistic' tests, respectively. This broad distinction appears in the neuropsychological literature, which reports that affective and linguistic prosody are often found to dissociate after unilateral brain damage (e.g. Heilman *et al.*, 1984). The *emotional tone* of human voices was assessed with the material of Scherer and Wallbott (1988). In this task, meaningless syllables are pronounced in 30 sentence-like formats (e.g.'fi get laich schong kil goster') by four actors (two male and two female) who attempted to convey five different emotional tones (joy, sadness, fear, anger and neutral). Subjects are required to indicate which emotion was conveyed by each sentence, by choosing the correct label among the five written possibilities. The linguistic aspect of speech prosody was assessed with: (i) *intonation* variations signalling declarative, imperative, exclamative and interrogative tone for 10 semantically neutral sentences (e.g. 'tu vas te coucher'—you are going to bed) pronounced by a female actor; the response mode was a four alternative forced-choice procedure; (ii) location manipulation of *silent pauses* in word-compounds (like in 'ba[]teaumouche' instead of 'bateau[]mouche'—plea[]sureboat' versus 'pleasure[]boat', where [] signals pause location); (iii) changes of pause locations within a clause (e.g. 'Il commençait à [] dormir lorsqu'on l'éveilla' instead of 'Il commençait à dormir [] lorsqu'on l'éveilla'—He was falling [] asleep when someone woke him up' versus 'He was falling asleep [] when someone woke him up'); For each of the two sub-tests, the pause was mislocated in half the trials. Subjects were required to judge whether the utterance sounded correct or not. (iv) changing the location of silent pauses in potentially ambiguous sentences (e.g.'Le garçon a dit [] le vieux est grand' versus 'Le garçon [] a dit le vieux [] est grand'—The boy said [] the old man is old' versus 'The boy [] said the old man [] is big', and then answer the question 'qui est grand?'—Who is big?'). C.N. was tested with all five tests while G.L. was only tested with the first two.

Results

C.N. matched 72% of the labels with the appropriate emotional tone. She performed as well as normal controls, with 73%. Thus, no disturbance was discernible in C.N.'s evaluation of the emotional tone of speech prosody. In matching intonation contours with labels, she obtained 23 out of 40 correct (57.5%, chance being 25%). Although her performance is above chance, it falls below normal range (26–30; mean 29). In the pause–location manipulation tests, C.N. scored eight out of eight at both the word level and the clause level. Nevertheless, she exhibited a deficit in the fifth test, when required to judge sentences that were syntactically potentially ambiguous; she scored 10 out of 16, when normal controls obtained 15 or 16 (mean 15.7).

G.L. encountered marked difficulties with the emotional test: he correctly matched 54.1% of the written labels. Although this performance is above a chance level of 20%, it cannot be considered normal. G.L. confused sadness with joy on several occasions, an error that was never made by any control nor by C.N. In contrast, he correctly matched the intonation contour to the appropriate label in 22 out of 40 trials (55%). This score is above chance and within the range of the controls' performance (22–30). Thus, G.L. does not appear to have particular difficulties with linguistic prosody, but suffers from an impairment in interpreting the emotional tone conveyed by prosodic cues.

Experiment 6: voice recognition and discrimination

Material and procedures

Three tests of famous voices were constructed with samples of the voices of famous public figures for (i) Belgian (40 samples) and (ii) Quebec (32 samples) inhabitants, that were edited so as to remove any word that could cue the speaker's professional activities [All samples were selected according to the patients' prior knowledge of the figures (which was checked with the identification of pictures or with correct descriptions of the physical appearance when presented with the written name).]; (iii) 15 samples of commercial recordings from three well-known French singers (Brel, Montand and Ferland) arranged in a 'pot-pourri', i.e. occurring in succession without any pause. Response mode was: (i) naming, (ii) multiple-alternative forced-choice and (iii) voice change detection. Discrimination of unfamiliar voices was assessed with the tests developed by Assal *et al.* (1976). These involve three conditions, all requiring a 'same–different' classification of two successive voice samples. In a given trial, the speaker produced the same sentence or two different sentences. Subjects were required to ignore the linguistic content and to attend to the voice. The voices were (i) from different sex mixed with voices from the same sex (30 trials); (ii) always from the same sex, among five female adults (30 trials); (iii) from the same sex but each being associated with a different accent (Japanese, German, English, Spanish and Italian; 30 trials).

Results

The results are summarized in Table 4. Compared with normal controls, both C.N. and G.L. showed impaired identification of speaking voices. The marked deficit observed in G.L.'s naming abilities might, however, be related to his residual word-finding difficulties. Yet, when given the opportunity to

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4 *Percentages of correct responses obtained on the voice recognition and discrimination tests by C.N. and by G.L., as well as the means of their matched controls' performance with their lowest and highest scores in parentheses*

	C.N.	C.N.'s controls		G.L.	G.L.'s controls	
Identification						
Famous speaking voices						
Naming	47.0	84.5	(66–94)	18.8	52.2	(41–66)
Name matching	—	—	—	75.0	93.4	(88–97)
Familiar singing voices	—	—	—	66.6	65.3	(33–100)
Discrimination						
Speakers of different sexes	100.0	100.0	—	100.0	100.0	—
Speakers of the same sex						
Test 1	70.0	100.0	—	70.0	100.0	—
Test 2	50.0	89.0	(73–100)	66.7	72.0	(57–87)
Speakers of the same sex but with different accents	60.0	91.7	(83–100)	66.7	82.7	(77–87)

match the voice to one of three written names, G.L. scored above chance but below normals ($P < 0.001$ by a binomial test). G.L. was less disturbed when having to identify his favourites (Montand and Brel).

In the discrimination of unfamiliar voices, both C.N. and G.L. obtained a perfect score when voices of speakers of different sexes were to be discriminated. When further tested with the condition involving five different female adults (test 2 in Table 4), G.L. scored within the normal range whereas C.N. performed at chance. Adding a foreign accent did improve C.N.'s but not G.L.'s performance. G.L.'s results contrasted with the average controls' scores, which were significantly higher in the discrimination of female speakers with differing accents than in the discrimination of female speakers with similar accents ($P < 0.05$, by a Wilcoxon signed ranks test). This lack of facilitation due to the presence of an accent confirmed our impression that G.L. did not discern the accents very well. G.L. was tested by different women having Quebec, French and Belgian accents. He could not tell the difference. Thus, it can be concluded that G.L. does not manifest any clear evidence of perceptual difficulties with voices, but he might well have an impairment in accent discrimination. C.N.'s results on the voice discrimination tasks were all below the normal range and, thus, indicate that she had perceptual difficulties with voices. This perceptual disorder might explain her trouble in identifying familiar voices (for considering perception and recognition of voices as separate abilities, *see* Van Lancker and Kreiman, 1987).

Experiment 7: singing and related expressive behaviour

Several attempts were made to assess C.N.'s singing, but she was very reluctant. We first asked her to sing any tune that she could remember. She could not do so. Then, we gave her the first lyrics of nine well-known nursery tunes. From the cue provided by the nine titles, which were immediately recognized by C.N., she attempted to recall five. For each of

Fig. 3 Examples of singing renditions of C.N.; **A** represents the best rendition of 'Frère Jacques' cued by lyrics, **B** corresponds to the second attempt, **C** refers to the rendition provided after having heard the model.

these songs, she made several attempts to sing them from memory. The scoring and the transcription of the singing material was performed by two independent professional musicians who did not know C.N. or the nature of her deficits. Consistency between their evaluation was very high; when a discrepancy occurred, it was recorded as such.

Considering only the best rendition, C.N. sang two fragments perfectly in tune. These allowed us to ascertain that C.N.'s singing abilities were excellent before her neurological accident. Nevertheless, analysis of her renditions was hampered by the large variability from one attempt to the next. A typical example is provided in Fig. 3. The first rendition of 'Frère Jacques' was perfect (*see* A in Fig. 3). However, after several attempts to sing other tunes, we asked C.N. to sing 'Frère Jacques' once more. This time the pitches were wandering (*see* B in Fig. 3). This inconsistency was also found when C.N. tried to repeat a model song (*see* C in Fig. 3).

Recall of the lyrics was also found to be deficient compared

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 5 *C.N.'s cued-recall of the lyrics of some well-known nursery tunes*

Title/first line	Recall	Real continuation
Au clair de la lune	Donne-moi ta plume	Mon ami Pierrot, Prête-moi ta plume
Sur le pont d'Avignon	On dansait	On y danse
Savez-vous planter des choux	À la mode	À la mode de chez nous
Meunier, tu dors	Ton moulin tourne	Ton moulin va trop vite
Alouette, gentille alouette	Je te plumerai le bec, la queue	Je te plumerai. Je te plumerai le bec? Je te plumerai le bec . . .
Frère Jacques	Dormez vous, Sonnez les matines, Ding dang dong	Frère Jacques Dormez vous, Dormez vous, Sonnez les matines, Sonnez les matines, Ding dang dong, Ding dang dong
Fais dodo, Colin mon p'tit frère	Papa est en haut, Maman est en bas, Tu auras du lolo	Fais dodo, t'auras du lolo, Papa est en haut, Il fait du gâteau, Maman est en bas, Elle fait du chocolat
Le bon roi Dagobert	A mis sa culotte à l'envers, S'en va't'en guerre	A mis sa culotte à l'envers, Le bon Saint Eloi . . .
Malbrough	A mis sa culotte à l'envers	S'en va't'en guerre
A la claire fontaine	En allant promener, J'ai trouvé l'eau si belle Que je m'y suis baigné, Jamais je ne l'oublierai	M'en allant promener, J'ai trouvé l'eau si belle Que je m'y suis baigné. Il y a longtemps que je t'aime, Jamais je ne t'oublierai

with normals (Peretz *et al.*, 1994). Examples of her recall performance are given in Table 5. When prompted with the title that corresponded to the first word(s), she could recall only a few additional words. More often than normal, these lyrics were not recalled verbatim as might be expected (Hyman and Rubin, 1990; Peretz *et al.*, 1994). Still, the data were found to be highly reliable. At re-test a year later, she provided the same kind of continuation. This result may indicate that lyrics from songs cannot be fully recalled without retrieval of their accompanying tune; only the gist of the lyrics, or their semantic content, can be retrieved. What is lacking is the temporal framework provided by the music to fill in the text details. This corresponds at least to her own introspective report: 'I am singing in my head, even if I know I don't have the right tune: that's the only way for me to find the lyric.'

Similar to C.N., G.L. was very reluctant to sing from memory. Yet, we noted that G.L. sang along spontaneously with some excitement when presented with certain well-known tunes that he could no longer overtly recognize, as previously described. This behaviour allowed us to collect some singing renditions. These were generally found to be rhythmically correct and to preserve the pitch contour of the model. In contrast, very few pitches were judged to respect the interval sizes, although these were tonally coherent. Therefore, G.L. generally sang in tune for our Western ears, even if he did not often respect the model (for more detailed data and discussion, *see* Peretz, 1993*a*). Thus, G.L. does not appear to suffer from a significant impairment in singing, except that he can no longer sing from memory.

Finally, it should be noted that C.N.'s *expressive* prosody was perhaps impaired as well. Her spontaneous speech sounded 'reserved' to us as well as to blind judges (i.e. her intonation in text reading was judged to be generally worse than that of matched controls). Yet, as mentioned previously, C.N. has suffered from chronic depression since her brain accident. This internal affective state may account for the impression of restrained intonation. In other words, it is difficult in C.N. to ascertain whether her expressive dysprosodia is the consequence of a general depressive state or the result of an insult to specific prosodic mechanisms. This issue is rendered particularly difficult by the fact that C.N.'s

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 6 *Summary of the results obtained by C.N. and G.L. on the tests used in the present study*

Tests	C.N.	G.L.
Audiometry	n	n
Intellectual abilities (WAIS)	n	n
Memory		
Wechsler scale	n	n
Warrington recognition memory tests	n	
Language		
BDAE or MT86β	n	n
Token test		n
Dichotic verbal discrimination	n	n
Familiar/unfamiliar spoken titles of songs	n	n-
Familiar/unfamiliar spoken lyrics	n	n
Familiar/unfamiliar written lyrics	n	n
Lyrics recall	n-	
Music		
Naming familiar tunes	—	—
Discrimination of familiar tunes	n-	
Familiar/unfamiliar tunes	—	m-
Discrimination of unfamiliar tunes: melodic differences	—	n-
Discrimination of unfamiliar tunes: rhythmic differences	n	n
Recognition of unfamiliar tunes	—	—
Pitch discrimination	n	n
Singing familiar tunes	—	—
Repeating familiar tunes	—	n-
Environmental sounds		
Naming familiar sounds	n	n
Naming familiar sounds from musical instruments	—	n-
Naming synthesized approximations of natural instruments	—	
Discrimination of synthesized approximations of natural instruments	n	
Speech prosody		
Labelling emotion	n	n-
Labelling intonation	n-	n
Pause location: word and clause level	n	
Pause location: syntactically ambiguous sentence level	—	
Human voices		
Naming famous speaking voices	n-	n-
Naming famous singing voices		n
Voice discrimination: gender difference	n	n
Voice discrimination: same gender	—	n
Voice discrimination: same gender, accent difference	n-	n-

n = normal; n- = below normal but above chance; — = chance

depression may not be related to her brain accident, although this is very likely.

Discussion

Following bilateral hemispheric strokes that involved portions of the left and right auditory cortices, C.N. and G.L. manifested irreversible auditory deficits that included the processing of music out of proportion to the processing of speech and environmental sounds. To summarize the main findings (Tables 6 and 7), both patients exhibited: (i) impaired recognition of familiar tunes; (ii) impaired discrimination of unfamiliar tunes on the basis of melody (i.e. pitch patterns); (iii) preserved discrimination of unfamiliar tunes on the basis of rhythmic patterns; (iv) normal recognition of environmental sounds; (v) impaired perception of speech prosody; (vi) impaired recognition of familiar voices; (vii) bilateral lesions of rostral auditory association cortex. C.N. but not G.L. manifested: (i) decreased sensitivity to pitch contour and interval distance as well as scale membership in the discrimination of unfamiliar musical sequences; (ii) impaired recognition of musical instrument sounds; (iii) impaired perception of linguistic information but not affective information conveyed by speech prosody; (iv) impaired

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 7 *Summary of the right and left hemispheric lesions (+) observed in C.N. and G.L.*

Lesion localization	C.N.		G.L.	
	Left	Right	Left	Right
Transverse gyrus of Heschl			+	
Superior temporal gyrus				
Rostral one-third	+	+	+	+
Middle one-third	+	+	+	
Caudal one-third			+	
Middle temporal gyrus	+	+	+	
Temporal pole	+	+	+	+
Inferior parietal lobule			+	
Frontal operculum		+	+	+
Insula		+	+	+

discrimination of unfamiliar voices. G.L. but not C.N. manifested: (i) normal sensitivity to pitch contour and distance in the discrimination of unfamiliar musical sequences; (ii) impaired perception of affective information but not linguistic information conveyed by speech prosody; (iii) normal discrimination of unfamiliar voices; (iv) extension of the left hemisphere lesion to the transverse gyrus of Heschl, caudal superior temporal gyrus cortex and inferior parietal lobule.

The classical taxonomy of cortical auditory disorders fails to capture the full spectrum of impairments in our two patients. Moreover, both patients suffered from specific musical disturbances that may lead to the observation of tune agnosia. In the following discussion, we will first consider implications of the present findings for the taxonomy of auditory agnosia and then for the current classification of musical disorders as well as for comprehension of *normal* musical cognition.

Taxonomy of auditory agnosia

Constructing a taxonomy might appear to be a rather theory-poor enterprise. However, independently motivated theories of auditory cognition are scarce in the non-verbal domain (for recent theoretical formulations, *see* Handel, 1989; Bregman, 1990). Consequently, a taxonomy of non-verbal auditory disorders caused by lesions of the cortex might provide a useful framework for developing such theories.

One major line of subdivision within auditory agnosia is between verbal and non-verbal pattern recognition. In verbal auditory agnosia, often referred to as 'pure word deafness', speech recognition is severely impaired, whereas the recognition of non-verbal material, such as musical tunes and environmental noises, remains intact (Bonvicini, 1905, cited in Ombredane, 1944; Albert and Bear, 1974; Saffran *et al.*, 1976; Coslett *et al.*, 1984; Metz-Lutz and Dahl, 1984; Yaqub *et al.*, 1988; Takahashi *et al.*, 1992). Conversely, there are cases of auditory agnosia in which the recognition of non-verbal patterns is obviously impaired, while the recognition of speech remains intact (Spreen *et al.*, 1965; Lambert *et al.*, 1989; Fujii *et al.*, 1990). The striking dissociation between music and speech documented in both of the present cases, specially in C.N., provides further support for this distinction. The observed dissociation included preserved recognition of lyrics despite impaired recognition of the accompanying tune played in isolation. This constitutes convincing support for domain specificity in auditory agnosia. The idea is not new, since early studies dealing with cerebral hemisphere differences have amply demonstrated the relevance of a verbal–non-verbal distinction as an important criterion for specialization in the auditory domain (e.g. Kimura, 1961, 1964; Milner, 1962; for an exhaustive review of this early literature, *see* Vignolo, 1969). Thus, the available neuropsychological data are largely consistent with the notion that the perception of speech and the perception of non-speech patterns are subserved by distinct neural systems, hence invalidating the claim that all auditory agnosia result from the disruption of a single general-purpose mechanism.

The other major line along which auditory agnosia is currently subdivided concerns the distinction between perception and recognition. This distinction echoes the apperceptive versus associative classification proposed by Lissauer (1890, 1988) to account for visual agnosia. According to this taxonomy, which is orthogonal to the verbal–non-verbal distinction, patients suffering from apperceptive agnosia can no longer recognize sound events because their perceptual analysis process is deficient. Conversely, patients suffering from associative agnosia can no longer recognize familiar sound events despite adequate analysis of the relevant features because access to memory representations is disturbed (for a comprehensive review, *see* Peretz, 1993*b*). Such dissociations have been originally documented for environmental sounds (Spinnler and Vignolo, 1966; Vignolo, 1982) and since then have been extended to the processing of human voices (Van Lancker and Kreiman,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

1987; Van Lancker *et al.*, 1988) and of familiar tunes (Eustache *et al.*, 1990).

According to this classical taxonomy of auditory agnosia, involving one dividing line between the verbal and non-verbal domains and another line between perception and representation, our two patients, C.N. and G.L., consist of two cases of apperceptive auditory agnosia. However, this classification is insufficient to capture the pattern of breakdowns observed in our two patients. Their data entail consideration of at least one novel neuropsychological condition within and apart from the non-verbal agnosia. This condition refers to the recognition of musical patterns, which is found to be disproportionally impaired relative to the recognition of both speech and environmental sounds. Had we limited our investigations to these three traditional domains—speech, music and environmental sounds—our two patients would represent pure cases of music agnosia.

There are several reasons that lead one to argue that musical patterns, unlike other familiar environmental sounds, are organized by procedures that are distinct and probably specific to the musical domain. One very likely level at which musical patterns are processed differently from both speech and environmental sounds is that of tonal encoding, as we have argued elsewhere (Peretz and Morais, 1989). This particular level is concerned with the mapping between pitch and musical scales, thus affording tonal coherence and reference points. Tonal encoding of pitch is specific to music and is essential for organizing most music of the Western idiom. Jackendoff (1987) conceives music specificity even earlier in the processing of musical information; he assumes that specificity takes place at the level of grouping mechanisms. Following both positions, assuming music-specific processing provides one with sufficient grounds to consider seriously that music is implemented in specialized neural systems.

In support of the claim that specific systems may underlie music perception (and hence result in patterns of breakdown that are limited to the musical domain) are the frequent reports of amusia without aphasia and aphasia without amusia (for an exhaustive and detailed review, *see* Dorgeuille, 1966). For example, in the auditory modality, several cases of amusia without speech comprehension deficits have been described (*see* Brazier, 1892, Pötzl and Uiberall, 1937 and Kleist, 1959, all reported in full in Dorgeuille, 1966). However, we do not know to what extent these patients encountered any difficulty with auditory patterns other than speech and music. Hence, the relevant information for the specificity of their musical impairments is lacking. The same limitation applies to the reverse cases of profound disturbances in speech comprehension, despite outstanding preserved musical perceptual abilities (Luria *et al.*, 1965; Assal, 1973; Basso and Capitani, 1985; Signoret *et al.*, 1987). These studies do not report results for non-verbal performance other than for music. The existence of a double dissociation between receptive aphasia and receptive amusia is compatible with the notion that auditory agnosia can be specific to music. However, it does not constitute proof.

Thus, the present cases, C.N. and G.L., who exhibit selective disturbance of music recognition abilities relative to those contributing to speech and environmental sound recognition, demonstrate that auditory agnosia requires subdivisions. Reverse cases of selective preservation of recognition abilities for musical patterns in the presence of profound disturbances of both speech and environmental sound recognition have been reported in one patient (Laignel-Lavastine and Alajouanine, 1921). The evidence is, however, weak, for only two well-known tunes were tested. These tunes might well have been picked up by mere guessing, as the authors themselves pointed out. Thus, the search of more robust cases of selective preservation for music should be the goal of future enquiry. The fact that selective loss of music exists, as it is observed in C.N. and G.L., renders the discovery of such case of selective preservation for music very likely.

Yet, we did not limit our investigation of C.N. and G.L. to music, speech and environmental sounds. We also investigated other areas of auditory cognition, such as speech prosody and voice recognition, that are usually treated in independent streams of research, under the labels of aprosodia and phonagnosia, respectively. However, both areas pertain to the non-verbal auditory domain, and as such, should be included in any investigation of auditory agnosia. The relevance of this claim is supported by the finding that processing aspects of both voice and prosody were found to be impaired to some extent in our patients.

There are basically two ways to interpret these associated impairments. One interpretation is that several different auditory modules are implemented in adjacent brain areas (or are highly interconnected) so that a lesion may well cut across these regions (or interrupt connections) and result in an assembled breakdown pattern of otherwise separate modules. We will refer to this explanation as the modular hypothesis. The alternative is to conceive the myriad of disorders as arising from disruption of a common mechanism, subserved by a single neuroanatomical substrate. In this account, functional dissociations would reflect an interplay between the extent of the damage and task difficulty; if the substrate is partially damaged, performance will be impaired for difficult tasks and spared for easy ones. We will refer to this explanation as the 'difficulty' hypothesis.

One major problem for the 'difficulty' hypothesis is that there are presently no objective criteria for domain complexity. Furthermore, there is already an argument against the 'difficulty' hypothesis available in the neuropsychological literature. This concerns the order in which tune and environmental sound recognition are recovered after generalized auditory agnosia. In one case (Mendez and Geehan, 1988, case 2), recovery started with environmental sounds and was followed by music. In another case (Motomura *et al.*, 1986), the reverse pattern was obtained, with the patient recovering

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

first music and then environmental sounds. The existence of these two opposite sequences of recovery is incompatible with the notion of a gradient of difficulty, for if there were such a gradient, the easiest domain should always recover first.

In order to evaluate the 'modular hypothesis', we shall consider how well it fits with the functional dissociations observed here and what sort of domain boundaries are implied by the present findings. First, the marked dissociation between music and environmental sound recognition observed in both patients indicates some processing autonomy between these two domains. Similarly, G.L.'s ability to recognize the musical timbre carrying a tune that itself could not be recognized argues for separability between musical instrument recognition and tune recognition. The same conclusion can be drawn from our observations concerning voice versus tune recognition. Mazzuchi *et al.* (1982) have previously reported a case, B.P., who showed the opposite pattern: B.P. failed to recognize familiar voices and some environmental sounds but was able to recognize familiar tunes.

The above dissociations are not too surprising when one considers the gross acoustic features that can distinguish the different sounds. Recognition of musical instruments is mainly timbre-dependent, whereas recognition of tunes is more pitch-dependent. Following this logic, one would not expect that recognition of musical instruments within a given class (e.g. strings, winds) would dissociate from recognition of voices belonging to adults of the same gender. Both are essentially timbre-based and require fine-grained distinctions among highly similar exemplars. Indeed, both categories were found to be impaired in C.N. and both were relatively spared in G.L. These findings support the similarity of the neuropsychological processes involved in recognizing certain aspects of human and musical sounds. This particular comparison is worthy of future enquiry.

Another important comparison concerns prosody and music. Analogies between prosody and music are compelling. For example, speech intonation contours and melodic contours are strikingly similar, both at a descriptive level and at a theoretical level (Thomassen, 1982; Dyson and Watkins, 1984). Thus, it is reasonable to postulate the existence of a common neural mechanism devoted to the processing of pitch contours for both speech and music. Hence, damage to this mechanism would be expected to produce similar impairments in both domains. However, neither case studied here exhibited comparable deficits in music perception and prosody perception. C.N. was unable to discriminate pitch variations in a musical context; yet, she was able to utilize syntactic and affective cues conveyed by the speech intonation contours. Conversely, G.L. retained normal use of vocal pitch changes as syntactic cues but not as emotional ones. More important, C.N. was found to deal adequately with temporal patterns in a musical context; yet, she encountered some difficulties in utilizing the syntactic cues provided by silent pauses in speech. Thus, these dissociations question the notion that common cortical mechanisms are mediating prosody and music processing.

The present results should be viewed more as incentives for carrying out systematic investigations than as definitive support for an alternative taxonomy of cortical auditory disorders. Still, the data in hand provide evidence for the ideas that (i) non-verbal auditory agnosia is not a homogeneous syndrome; (ii) the observed functional dissociations emerged as the result of damage to specialized neural subsystems that lie in anatomical proximity within the superior temporal region, not as the result of partial damage to a single neural system.

Classification of musical disorders and implications for normal musical cognition

Apart from suggesting further subdivisions of non-verbal auditory agnosia, the present findings bear on our understanding of normal tune recognition and on the classification of music-related disorders caused by cortical lesions. Two observations are particularly noteworthy. One concerns the finding that perception of melodic patterns (i.e. sequential pitch variations) can be disturbed without an associated deficit in the perception of rhythmic patterns (i.e. sequential temporal variations), and yet a severe impairment of familiar tune recognition may result. A second point that entails revision of models of normal auditory cognition is that recognition of familiar tunes can be disrupted without an associated deficit in the recognition of familiar lyrics.

Dissociation between melody and rhythm

The observed dissociation between the perception of melodic patterns and rhythmic patterns has been previously reported in patients with unilateral hemispheric lesions (Peretz, 1990). These data indicated that different neural subsystems mediate the perception of melodic and rhythmic patterns, at least at some early stage in the processing of musical sequences (Peretz and Kolinsky, 1993). The evidence is not limited to auditory functions, for similar dissociations have been observed in other spheres of musical behaviour such as singing (Dorgeuille, 1966; Brust, 1980; Mavlov, 1980) and reading (Dorgeuille, 1966; Assal, 1973; Brust, 1980). Thus, the distinction between neural subsystems governing melodic and rhythmic pattern perception applies to both receptive and expressive functions, and the present findings are consistent with a major division between amelodia and arrhythmia in amusia.

Relationship between melody perception and tune recognition

The present observations raise the possibility that impaired perception of melodic patterns, not impaired perception of rhythmic patterns, underlies tune agnosia. C.N. and G.L.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

were both impaired in discriminating melodic patterns but could process rhythmic ones; and both patients could not recognize tunes that should have been familiar. Several previous investigations, including one by the first author, suggest, however, that poor discrimination of melodic patterns does not invariably result in impaired recognition of tunes. Patients with unilateral (right or left) hemispheric lesions who manifested decreased sensitivity to melodic variations were found to be able to determine whether a novel tune had been presented in prior trials (Peretz, 1990). Conversely, cases in which familiar tunes could not be recognized but changes in unfamiliar tunes could be detected have been reported (Lamy, 1907; Eustache *et al.*, 1990, case 1). Although discriminations of the kind used in the present study were not evaluated by Lamy or Eustache *et al.*, their observations suggest that tune agnosia can occur without associated impairments involving melody discrimination. Furthermore, C.N. and G.L. did not suffer exclusively from perceptual disturbances: neither could recall and sing a tune on command; this suggests that retrieval as well as encoding mechanisms were disturbed in both cases. Thus, the present cases do not constitute unequivocal evidence regarding the possibility that access to stored representation of tunes is determined by (intact) melodic computation.

One implication of the observed deficits in encoding and retrieving familiar tunes concerns their classification according to the taxonomy of cortical auditory disorders. The occurrence of a deficit at the level of stored representations of tunes renders a simple 'receptive–expressive' dichotomy problematic, since both listening to and singing of familiar songs involves the activation of memory representations. Thus, any impairment in the tune representation system would cut across modalities. This problem in classification is not limited to music-related deficits. For example, whether degradation in the lexico-semantic system compromises both comprehension and expression of speech remains controversial (*see*, for example, the special issue of *Cognitive Neuropsychology* devoted to this question in 1988).

Dissociation between memory for tune and lyrics

C.N. quickly and accurately recognized the lyrics of familiar tunes even though she was unable to recognize the corresponding tune. Similarly, G.L. performed well above chance on the lyrics recognition tests but only slightly above chance and far worse than normals on tune recognition tests. Furthermore, on one occasion, C.N. produced two mismatched songs (e.g. singing 'le bon roi Dagobert' with the tune of 'Il était une bergère'). This dissociated behaviour observed in both C.N. and G.L. suggests that memory for lyrics and memory for tunes are subserved by separate representations. Support for this claim is provided by observation of the reverse dissociation in cases of pure word deafness (e.g. Laignel-Lavastine and Alajouanine, 1921; Yaqub *et al.*, 1988).

The results of studies in normal subjects have been interpreted as evidence that representations of melody and lyrics are not separate but integrated in song memory (Serafine *et al.*, 1984, 1986; Crowder *et al.*, 1990). The conflict between the latter conclusion and ours most likely arises from methodological differences. For example, Serafine *et al.* used a forced-choice procedure in which subjects were required to recognize the tune, the lyrics or both of novel songs that they had previously heard; among the alternatives were excerpts in which the tune of one sample and the lyrics of another were combined. Given novel, interfering material among the response choices, subjects may have formed integrated representations of tune and lyrics in their memories in order to facilitate recognition. Such a strategy is poorly suited for recognition of well-known songs, which are typically built around a few melodic lines, each of which can carry different lyrics. Consequently, encoding the tune and lyrics independently would be both parsimonious and efficient.

Neural correlates

A final point concerns the pathoanatomical correlates of the observed auditory deficits. Given the rarity of naturally occurring bilateral lesions of superior temporal cortex in the absence of associated dementia or persistent aphasia, the present cases provided an unusual opportunity to examine the functional effects of bilateral auditory cortex lesions in humans. Common to both cases was damage to the left and right rostral superior temporal gyri. On the basis of cytoarchitectural features in humans (Galaburda and Sanides, 1980) and presumably homologous connectivity patterns (e.g. Galaburda and Pandya, 1983) and electrophysiological response properties (e.g. Merzenich and Brugge, 1973) in non-human primates, this portion of superior temporal cortex encompasses several auditory association areas (for review, *see* Tramo *et al.*, 1990). Since C.N. did not appear to sustain damage to the transverse gyrus of Heschl in either hemisphere, the present findings suggest that bilateral, partial lesions of auditory association cortex that spare primary auditory cortex are sufficient to impair melody discrimination, tune recognition, voice recognition and perception of speech prosody. Deficits in auditory sequence discrimination following selective, bilateral ablations of the superior temporal gyrus that were designed to spare primary auditory cortex have been reported in non-human primates (Dewson *et al.*, 1970; Cowey and Weiskrantz, 1976; Colombo *et al.*, 1990). In humans, impaired discrimination of unfamiliar pitch patterns has been reported in populations of seizure patients with unilateral excisions of the right rostral temporal lobe that included rostral auditory association cortex as well as epileptogenic medial temporal structures (Milner, 1962; Zatorre, 1985); in either the left or right hemisphere, caudal extension of the excision into the transverse gyrus of Heschl, which probably houses primary auditory cortex, caused a deficit that was independent from, but additive with, the deficit caused by excision of right rostral auditory association cortex. Increased cerebral blood flow in the right superior temporal gyrus (and right fusiform gyrus) has recently been

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

reported in normal subjects who were passively listening to unfamiliar pitch patterns (Zatorre *et al.*, 1994). Impaired recognition of unfamiliar pitch patterns has been reported following left or right excisions of the rostral temporal lobe; extension of the excision into the transverse gyrus did not produce additional recognition deficits (Zatorre, 1985). A few cases of impaired voice recognition following unilateral right or bilateral hemispheric strokes that involved the superior temporal region have been reported previously (Van Lancker *et al.*, 1988). In G.L., the caudal extension of the left hemisphere lesion into the transverse gyrus and caudal superior temporal gyrus probably accounts for the speech recognition deficits observed in the acute and subacute stages following his second stroke. It is not possible to account for the other, relatively minor differences in auditory functions between C.N. and G.L. on the basis of the observed pathoanatomical differences; limitations in the sensitivity of our imaging technique to structural damage and physiological derangement, differences in the timing of the experimental observations relative to the times of stroke onsets and inter-individual differences in structure–function relationships are possible contributing factors. Future studies in neurological patients that combine experimental measurements of a wide range of auditory processes with *in vivo* brain imaging are needed to advance our knowledge about cortical auditory disorders and, in turn, the cerebral organization of higher auditory functions.

Acknowledgements

We wish to thank Roland De Beuckelaer, Marie-Josée Coeckaerts, Jeanine Deleval and Anne Leonard for the speech evaluation, Sergio Hassid for the audiological examination, Agnès Dewier for the initial psychological evaluation of C.N., Françoise Cot for the speech evaluation and Myriam Babaï, Sylvie Hébert, Lise Gagnon, Marc Filaretos and Hélène Pineau for help in constructing the material for G.L. We also wish to thank Maryse Lassonde for comments with great insight made on an earlier draft of this paper, and an anonymous reviewer for most helpful suggestions. Above all, we are especially indebted to C.N. and to G.L. for their precious collaboration. This research was supported by a fellowship and research grant from the Natural Sciences and Engineering Research Council of Canada to Isabelle Peretz, and by a DHHS grant from the NIH National Institute on Deafness and Other Communication Disorders to M. Tramo. R. Kolinsky is a research associate of the Belgian National Funds for Scientific Research.

References

Albert ML, Bear D. Time to understand. A case study of word deafness with reference to the role of time in auditory comprehension. Brain 1974; 97: 373–84.

Assal G. Aphasie de Wernicke sans amusie chez un pianiste. Rev Neurol (Paris) 1973; 129: 251–5.

Assal G, Zander E, Kremin H, Buttet J. Discrimination des voix lors des lésions du cortex cérébral. Schweiz Arch Neurol Neurochir Psychiatr 1976; 119: 307–15.

Auerbach SH, Allard T, Naeser M, Alexander MP, Albert ML. Pure word deafness. Analysis of a case with bilateral lesions and a defect at the prephonemic level. Brain 1982; 105: 271–300.

Basso A, Capitani E. Spared musical abilities in a conductor with global aphasia and ideomotor apraxia. J Neurol Neurosurg Psychiatry 1985; 48: 407–12.

Béland R, Lecours AR. The MT-86β aphasia battery: a subset of normative data in relation to age and level of school education. Aphasiology 1990; 4: 439–62

Berthier JE. 1000 chants. Les Presses d'Ile-de-France, 1979.

Bregman AS. Auditory scene analysis. The perceptual organization of sound. Cambridge (MA): MIT Press, 1990.

Brel J. Jacques Brel: oeuvre intégrale. Paris: Laffont, 1982.

Brust JC. Music and language: musical alexia and agraphia. Brain 1980; 103: 367–92.

Buchman AS, Garron DC, Trost-Cardamone JE, Wichter MD, Schwartz M. Word deafness: one hundred years later. J Neurol Neurosurg Psychiatry 1986; 49: 489–99.

Buchtel HA, Stewart JD. Auditory agnosia: apperceptive or associative disorder? Brain Lang 1989; 37: 12–25.

Celesia GG. Organization of auditory cortical areas in man. Brain 1976; 99: 403–14.

Colombo M, D'Amato MR, Rodman HR, Gross CG (1990) Auditory association cortex lesions impair auditory short-term memory in monkeys. Science 1990; 247: 336–8.

Coslett HB, Brashear HR, Heilman KM. Pure word deafness after bilateral primary auditory cortex infarcts. Neurology 1984; 34: 347–52.

Cowey A, Weiskrantz L. Auditory sequence discrimination in Macaca mulatta: the role of the superior temporal cortex. Neuropsychologia 1976; 14: 1–10.

Crowder RG, Serafine ML, Repp B. Physical interaction and association by contiguity in memory for the words and melodies of songs. Mem Cognit 1990; 18: 469–76.

Damasio H, Damasio AR. Lesion analysis in neuropsychology. New York: Oxford University Press, 1989.

De Renzi E, Faglioni P. Normative data and screening power of a shortened version of the Token Test. Cortex 1978; 14: 41–9.

Dewson JH 3d, Cowey A, Weiskrantz L. Disruptions of auditory sequence discrimination by unilateral and bilateral cortical ablations of superior temporal gyrus in the monkey. Exp Neurol 1970; 28: 529–48.

Dorgeuille C. Introduction à l'étude des amusies. [Dissertation]. Paris, 1966.

Dyson MC, Watkins AJ. A figural approach to the role of melodic contour in melody recognition. Percep Psychophys 1984; 35: 477–88.

Eustache F, Lechevalier B, Viader F, Lambert J. Identification and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

discrimination disorders in auditory perception: a report on two cases. Neuropsychologia 1990; 28: 257–70.

Freud S. Zur Auffassung der Aphasien: eine Kritische Studie. Wien: Franz Deuticke, 1891.

Fujii T, Fukatsu R, Watabe S, Ohnuma A, Teramura K, Kimura I, et al. Auditory sound agnosia without aphasia following a right temporal lobe lesion [published erratum appears in Cortex 1990; 26: 672]. Cortex 1990; 26: 263–8.

Galaburda AM, Pandya DN. The intrinsic architectonic and connectional organization of the superior temporal region of the rhesus monkey. J Comp Neurol 1983; 221: 169–84.

Galaburda A, Sanides F. Cytoarchitectonic organization of the human auditory cortex. J Comp Neurol 1980; 190: 597–610.

Goodglass H, Kaplan E. The assessment of aphasia and related disorders. Philadelphia: Lea & Febiger, 1972.

Grison B. Une étude sur les altérations musicales au cours des lésions hémisphériques [thèse]. Paris, 1972. [Cited by Benton AL. The amusias. In: Critchley M, Henson RA, editors. Music and the brain. London: Heinemann, 1977: 378–97.]

Handel S. Listening. An introduction to the perception of auditory events. Cambridge (MA): MIT Press, 1989.

Heilman KM, Bowers D, Speedie L, Coslett HB. Comprehension of affective and nonaffective prosody. Neurology 1984; 34: 917–21.

Hyman IE Jr, Rubin DC. Memorabeatlia: a naturalistic study of long-term memory. Mem Cognit 1990; 18: 205–14.

Jackendoff RS. Consciousness and the computational mind. Cambridge (MA): MIT Press, 1987.

Kimura D. Cerebral dominance and the perception of verbal stimuli. Can J Psychol 1961; 15: 166–71.

Kimura D. Left-right differences in the perception of melodies. Q J Exp Psychol 1964; 16: 355–8.

Laignel-Lavastine M, Alajouanine T. Un cas d'agnosie auditive. Rev Neurol (Paris) 1921; 28: 194–8.

Lambert J, Eustache F, Lechevalier B, Rossa Y, Viader F. Auditory agnosia with relative sparing of speech perception. Cortex 1989; 25: 71–82.

Lamy H. Amnésie musicale chez un aphasique sensoriel, ancien professeur de musique. Conservation de l'execution, de la lecture, de l'improvisation et de la composition. Rev Neurol (Paris) 1907; 15: 688–93.

Lechevalier B, Rossa Y, Eustache F, Schupp C, Boner L, Bazin C. Un cas de surdité corticale épargnant en partie la musique. Rev Neurol (Paris) 1984; 140: 190–201.

Liegeois-Chauvel C, Musolino A, Chauvel P. Localization of the primary auditory area in man. Brain 1991; 114: 139–51.

Lissauer H. Ein Fall von Seelenblindheit nebst einem Beitrage zur Theorie derselben. Arch Psychiatr Nervenkr 1890; 21: 222–70.

Lissauer H. A case of visual agnosia with a contribution to theory. Cognit Neuropsychol 1988; 5: 157–92.

Luria A, Tsvetkova L, Futer J. Aphasia in a composer. J Neurol Sci 1965; 2: 288–92.

Matsui T, Hirano A. An atlas of the human brain for computerized tomography. Tokyo: Igaku-Shoin, 1978.

Mavlov L. Amusia due to rhythm agnosia in a musician with left hemisphere damage: a non-auditory supramodal defect. Cortex 1980; 16: 321–8.

Mazzucchi A, Marchini C, Budai R, Parma M. A case of receptive amusia with prominent timbre perception defect. J Neurol Neurosurg Psychiatry 1982; 45: 644–7.

Mendez MF, Geehan GR Jr. Cortical auditory disorders: clinical and psychoacoustic features. J Neurol Neurosurg Psychiatry 1988; 51: 1–9.

Merzenich MM, Brugge JF. Representation of the cochlear partition of the superior temporal plane of the macaque monkey. Brain Res 1973; 50: 275–96.

Metz-Lutz MN, Dahl E. Analysis of word comprehension in a case of pure word deafness. Brain Lang 1984; 23: 13–25.

Milner B. Laterality effects in audition. In: Mountcastle VB, editor. Interhemispheric relations and cerebral dominance. Baltimore: Johns Hopkins University Press, 1962: 177–95.

Motomura N, Yamadori A, Mori E, Tamaru F. Auditory agnosia: analysis of a case with bilateral subcortical lesions [published erratum appears in Brain 1986; 109: 1322]. Brain 1986; 109: 379–91.

Oldfield RC. Handedness in musicians. Br J Psychol 1969; 60: 91–9.

Ombredane A. Perception et langage. Etudes de psychologie médicale. Tome I. Rio de Janeiro: Atlantica editera, 1944.

Pandya DN, Yeterian EH. Architecture and connections of cortical association areas. In: Peters A, Jones EG, editors. Cerebral cortex, Vol. 4. New York: Plenum Press, 1985: 3–61.

Peretz I. Processing of local and global musical information by unilateral brain-damaged patients. Brain 1990; 113: 1185–205.

Peretz I. Auditory atonalia for melodies. Cogn Neuropsychol 1993a; 10: 21–56.

Peretz I. Auditory agnosia: a functional analysis. In: McAdams S, Bigand E, editors. Thinking in sound. The cognitive psychology of human audition. Oxford: Clarendon Press, 1993b: 199–230.

Peretz I, Kolinsky R. Boundaries of separability between melody and rhythm in music discrimination: a neuropsychological perspective. Q J Exp Psychol [A] 1993; 46: 301–25.

Peretz I, Morais J. Music and modularity. Contemp Mus Rev 1989; 4: 277–91.

Peretz I, Babaï M, Lussier I, Hébert S, Gagnon L. Corpus d'extraits musicaux: indices relatifs à la familiarité, à l'âge d'acquisition et aux évocations verbales. Can J Psychol 1994. In press.

Saffran EM, Marin OSM, Yeni-Komshian GH. An analysis of speech perception in word deafness. Brain Lang 1976; 3: 209–28.

Scherer K, Wallbott H. Development of a standardized vocal emotion recognition test [unpublished manuscript]. 1988.

Serafine ML, Crowder RG, Repp BH. Integration of melody and text in memory for songs. Cognition 1984; 16: 285–303.

Serafine ML, Davidson J, Crowder RG, Repp BH. On the nature of melody-text integration in memory for songs. J Mem Lang 1986; 25: 123–35.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Signoret JL, Van Eeckhout P, Poncet M, Castaigne P. Aphasie sans amusie chez un organiste aveugle. Rev Neurol (Paris) 1987; 143: 172–81.

Spinnler H, Vignolo LA. Impaired recognition of meaningful sounds in aphasia. Cortex 1966; 2: 337–48.

Spreen O, Benton AL, Fincham RW. Auditory agnosia without aphasia. Arch Neurol 1965; 13: 84–92.

Takahashi N, Kawamura M, Shinotou H, Hirayama K, Kaga K, Shindo M. Pure word deafness due to left hemisphere damage. Cortex 1992; 28: 295–303.

Talairach J, Tournoux P. Co-planar stereotaxic atlas of the human brain. Stuttgart: Thieme, 1988.

Tanaka Y, Yamadori A, Mori E. Pure word deafness following bilateral lesions. A psychophysical analysis. Brain 1987; 110: 381–403.

Thomassen J. Melodic accent: experiments and a tentative model. J Acoust Soc Am 1982; 71: 1596–605.

Tramo MJ, Bharucha JJ, Musiek FE. Music perception and cognition following bilateral lesions of auditory cortex. J Cogn Neurosci 1990; 2: 195–212.

Van Lancker D, Kreiman J. Voice discrimination and recognition are separate abilities. Neuropsychologia 1987; 25: 829–34.

Van Lancker DR, Cummings JL, Kreiman J, Dobkin BH. Phonagnosia: a dissociation between familiar and unfamiliar voices. Cortex 1988; 24: 195–209.

Vignolo LA. Auditory agnosia: a review and report of recent evidence. In: Benton AL, editor. Contributions to clinical neuropsychology. Chicago: Aldine, 1969: 172–208.

Vignolo L. Auditory agnosia. Philos Trans R Soc Lond Biol 1982; 298: 49–57.

Wexler B, Halwes T. Increasing the power of dichotic methods: the fused rhymed words test. Neuropsychologia 1983; 21: 59–66.

Yaqub BA, Gascon GG, Al-Nosha M, Whitaker H. Pure word deafness (acquired verbal auditory agnosia) in an Arabic speaking patient. Brain 1988; 111: 457–66.

Zatorre RJ. Discrimination and recognition of tonal melodies after unilateral cerebral excisions. Neuropsychologia 1985; 23: 31–41.

Zatorre RJ, Evans AC, Meyer E. Neural mechanisms underlying melodic perception and memory for pitch. J Neurosci 1994; 14: 1908–19.

Received February 1, 1994. Revised May 24, 1994. Accepted June 21, 1994

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.