

Review Article

Musical Processing in the Brain: A Neuropsychological Approach through Cases with Amusia

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Abstract

Over the last decade, a considerable number of studies have been made on the cognitive processing of music. In this review, I discuss the cognitive processing of music based on the findings of our amusic cases. A patient with pure amusia (case 1) due to infarction of the anterior portion of the bilateral temporal lobes revealed a disturbance in the discrimination of chords. The patient also showed an impairment in singing familiar songs, along with the replacement of phrases (*paramelodia*). My positron emission topography (PET) study, which investigated the brain regions participating in chord perception, showed bilateral activation of the anterior portion of the temporal lobes. From the results of this clinical case and PET study, I can reasonably conclude that these brain regions have a relationship with chord perception. The second patient (case 2) had a large infarction of the bilateral temporal lobes, and also exhibited word deafness, environmental sound agnosia and receptive and expressive amusia. Though the patient produced normal scores in tasks of chord and pitch discrimination, the recognition of tonality was impaired. It was suggested that tonality might be one of the independent factors for receptive processing of music. From these findings, some characteristic symptoms of amusia are described, and I present a diagram regarding musical processing in the brain.

Keywords: Amusia; Neuropsychology; Paramelodia; Conduction Amusia; Chord

Introduction

It is often said that music has no borders. It is also a fact that there are differences in the style and content of music, depending on the culture and the era. However, among members of the same culture, music can evoke the same feeling immediately and easily. For example, adults who live in cultural areas related to western music need less than 0.25 seconds to identify whether the music is happy or sad [1]. This nature of music is assumed to be useful to the adaptation of living in human society. Music can act as a strategy for non-verbal communication, to associate citizens and to facilitate the unity of a group. In this process, two components of music (pitch and rhythm) are thought to play an important role. When some tones sound with a specific frequency ratio, these tones make a consonance. Moreover, the regularity of time makes the movements of most people synchronize, as in dancing [2]. Therefore, one way to know how music is recognized and represented in the brain may be to understand the relationship between human behavior and the brain. In this review, I describe two cases of amusia who showed the impairment of musical ability due to the brain damage, and propose some aspects about the perception and coding of music in the brain.

Amusia**Definition of amusia**

It is widely accepted that neuropsychology began from the first case report of aphasia by Broca. A few years later, it was reported that not only language but also music was impaired by brain damage [3].

A musician with aphasia could not read a musical score [3] or hum a tune [3]. The concept of amusia appeared on the stage.

Amusia is defined as an acquired deficit of music processing [4]. In musicology, it is thought that melody, rhythm, and harmony are the three basic components of music. Melody is the tonal sequence made up of changes in pitch and rhythm, which are integrated into an entity. In other words, I can say that these three components are pitch, rhythm and harmony. As mentioned below, tonality is sometimes regarded as another component of music [5,6]. Because several cases with pure amusia, meaning the sole impairment of musical ability without affecting the other cognitive functions, have been reported, it was supposed that music has an independent processing in the brain, at least to some extent [7].

Diagnosis and categorization of amusia

Musical ability consists of the perception of the basic components (such as pitch and rhythm), the singing and playing of musical instruments, the reading and writing of musical scores and musical appreciation with emotional experiences [8,9]. When one or more of these abilities are impaired by brain damage, dysfunctionality, and influences of drugs, the patient is diagnosed with amusia.

The categorization of amusia corresponds to that of aphasia (Figure 1). Amusia is generally classified as one of two types, receptive or expressive [10,11]. Receptive amusia specifies an inability to remember (amnestic amusia), read (musical alexia) or understand music (narrow receptive amusia), while expressive amusia indicates

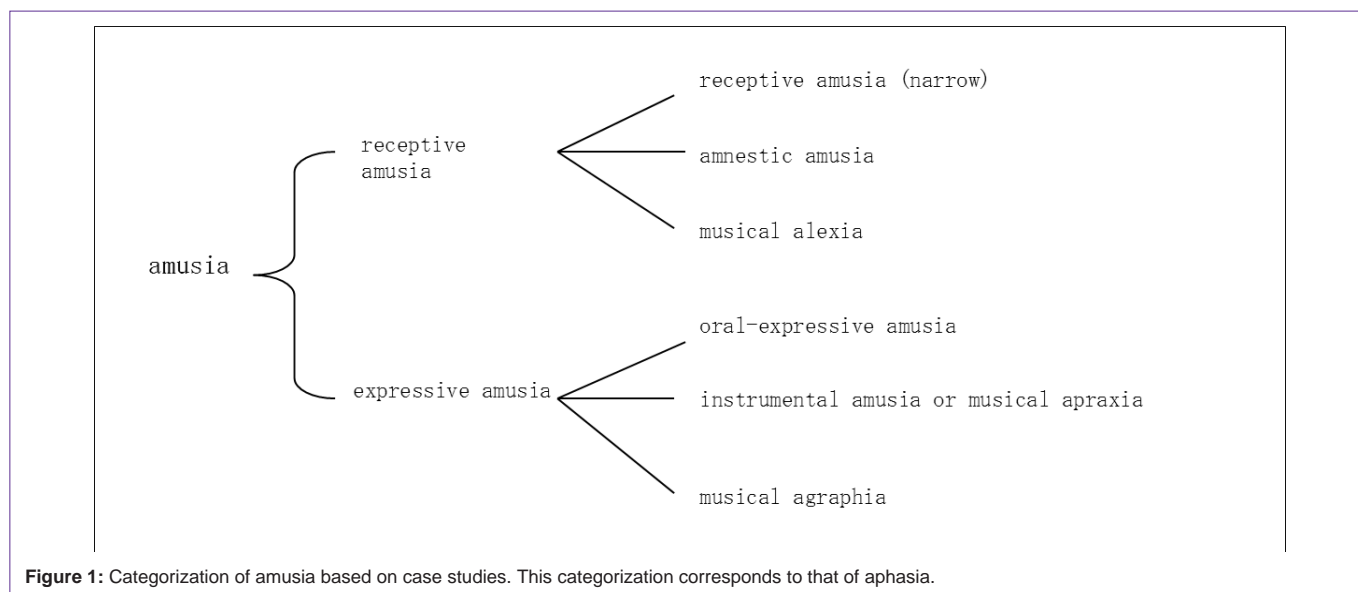


Figure 1: Categorization of amusia based on case studies. This categorization corresponds to that of aphasia.

difficulty in singing (oral-expressive amusia) writing music (musical agraphia), or in instrumental performance (instrumental amusia or musical apraxia) [12]. In reported cases of receptive amusia, the degree of the impairment of pitch and rhythm are different in their severity, suggesting that perception of these two music components occurs independently in the brain [13]. Studies of expressive amusia have shown that the degree of the impairment differs between singing and instrument playing [14], thus expressive amusia is often subdivided into vocal and instrumental motor amusia.

Peretz [15] suggested that tonality was an independent component of musical perception. She examined in detail a patient with amusia due to a bilateral infarction of the temporal lobes. The patient was unable to perceive sequential pitch structure, particularly when pitch intervals required tonal interpretation, in the presence of accurate encoding of melodic contour and of interval sizes. Peretz concluded that the impairment of her patient derived from auditory atonalia as a consequence of brain damage. Further, I experienced a patient with an infraction of bilateral temporal lobes who showed an impairment of melody perception, though the ability of tonality perception was preserved [6]. By comparing the results of our patient with those of Peretz' patient [15], I can identify a double dissociation between the impairment of tonality and of other musical components. The patient reported by Peretz had an impairment of tonality with the absence of perception of melody, whereas my patient retained the feeling of tonality with an impairment of perception of melody and chord. This double dissociation revealed that tonality might be an independent component of the perception of music [6].

Reported literature cases of amusia

There are fewer than one hundred amusic cases in the literature. Among them, about fifty cases had detailed descriptions of symptoms, findings and sites of lesions. There are more cases with left than right hemisphere lesions, because in many cases functional differences between language and music in aphasia were investigated, though musical ability could be completely preserved

despite aphasia. Therefore, the left dominance of the reported cases does not necessarily demonstrate that amusia is more likely to occur via left hemisphere lesions. Most of the reported amusic cases were professional musicians or talented amateur musicians who possessed high levels of musical ability. Almost all of the amusic cases in the literature had multiple impairments of cognitive function other than music, and it could not be determined to what extent these impairments affected the occurrence of amusia. Further, the discrimination of the lesions responsible for amusia from those related to other cognitive dysfunctions was impossible. Therefore, I may reasonably conclude that cases of pure amusia can best reveal the relationship between amusic symptoms and responsible lesions more clearly and directly. There are only eight reported cases with pure amusia (Table 1). The typical case of pure amusia was twenty years old amateur guitarist who showed receptive and expressive amusia after cerebral hemorrhage from arteriovenous malformation (AVM). Due to the damage of posterior portion of left superior temporal gyrus, he complained that musical tones sound the same and unmusical, and songs sound like a screaming voice. In addition to the close examination of musical ability, the authors explored other cognitive functions in detail of the memory, attention, visuospatial function, praxis, psychomotor integration, and intellectual processes, all of which were within normal limits. Based on the cases of pure amusia shown in the Table 1 and reported amusic cases with other cognitive impairments, there is a fairly general agreement regarding the cognitive processing of music in the brain as follows: i) cognitive processing of music and language share a common neural pathway, at least partially, ii) in amusic cases, impairments in pitch are more common than impairments in rhythm, iii) the impairment of musical expression (expressive amusia) such as singing and instrumental playing tend to be caused by damage of the right hemisphere, and iv) receptive amusia is caused by the damage of right or bilateral temporal lobe(s).

Cases of amusia

Regarding musical processing in the brain, I had the opportunities

Table 1. Summary of reported cases with pure amusia.

Author	Year	Journal	Patient	Musical history	Diagnosis	Site of lesion	CT/MRI	Chief complaints	Findings related to music
McFarland	1982	Arch Neurol	78 y.o., M, R	Amateur organist	Infarction	Superior portion of right temporal lobe ~supramarginal gyrus	CT	Impairment of playing the organ	Possible to sing and reproduce rhythm, and to recognize musical instruments and types of music. Unable to play melodies and their rhythm patterns on the organ.
Takeda	1990	Rinsho-shinkei	65 y.o., F, L	Teacher of Shamisen (Japanese traditional string instrument)	Haemorrhage	Right superior temporal gyrus ~ subcortical region of Heschl gyrus	CT/MRI	Unable to sing familiar folk songs	Able to recognize folk songs. In the Seashore test, only the result of tonal memory test was slightly decreased. The pitch of singing was incorrect, but improved with accompaniment.
Peretz	1994	Brain	CN: 35 y.o., F, R	None (nurse)	Infarction (post-clipping of bilateral MCA)	Anterior portion of bilateral temporal lobes, right insular, right inferior temporal gyrus	CT	Unable to recognize and sing familiar songs	Normal in rhythm recognition. Impairment of the recognition of familiar music, melodic contour, pitch interval, and musical instruments. Dysprosodia in speech.
Piccirilli	2000	JNNP	20 y.o., M, R	Amateur guitarist	Haemorrhage from AVM	Posterior portion of left superior temporal gyrus	MRI	Musical tones sound the same and sound unmusical. Songs sound like a screaming voice.	Impairment of the recognition of familiar melodies. In the Bentley's test, tonal memory was impaired. Impairment of guitar performance. Normal recognition and reproduction of rhythm.
Satoh	2005	Cortex	70 y.o., F, R	None (chorus club)	Infarction	Anterior portion of bilateral temporal lobes	MRI	Unable to recognize familiar music. Songs were heard out of tune.	Impairment of the recognition of familiar melodies and correct-false discrimination. In the Seashore test, tonal memory was impaired. The same-different discrimination of chords was impaired. Normal in rhythm discrimination. Replaced melody in singing familiar songs.
Terao	2006	Neuropsychologia	62 y.o., F, R	Professional tango dancer	Infarction	Right superior temporal gyrus ~ Heschl gyrus, inferior parietal region, posterior portion of posterior central gyrus, posterior portion of insular	MRI	Unable to sing well as a professional singer	All results of Seashore test were decreased, especially timbre, loudness, and pitch test. Unable to discriminate differences in semitone. In singing, unable to keep the same pitch, and the pitch irregularly fluctuated.
Barquero	2010	J Neurol	53 y.o., F, R	Pianist, musical critic	FTLD	Atrophy of bilateral frontal and temporal lobes (L>R)	MRI	Unable to appreciate the quality of musical performances	Good performance in piano playing. Unable to appreciate the quality of performances, and to discriminate the performance between professional pianist and beginner. Normal recognition of melody, pitch, rhythm, and tempo, and of detecting the false tone in a familiar melody.
Hochman	2014	J Stroke Cerebrovas Dis	61 y.o., M, R	None (optometrist)	Infarction	Right temporoparietal cortex, right insula	MRI	Unable to sing his familiar song on the car radio which he had lifelong always sung in tune.	Singing along to classic rock songs on his car radio off pitch

Table 1. Summary of reported cases with pure amusia (continued).

Author	Year	Amusia	Cognitive function	Other findings	Appendix
McFarland	1982	Expressive (instrumental amusia)	At the first neurological examination two weeks later the infarction, he forgot familiar names. But, a month later, the results of Boston Diagnostic Aphasia Examination were normal.	Slight astereognosia in left hand.	Since the cerebrovascular accident, the patient could not read or write musical scores.
Takeda	1990	Expressive (singing)	Aphasia, agraphia, acalculia, and apraxia were not observed. WAIS: VIQ 116, PIQ 108.	None.	The musical background of the patient was traditional Japanese music. It is unclear if we can interpret the results with those of cases with a western musical background.
Peretz	1994	Receptive + expressive	The results of Boston Diagnostic Aphasia Examination were perfect. WAIS-R: VIQ 103, PIQ 94, TIQ 98. WMS 103.	Olfactory disturbance.	The CT images were unclear, so we could not precisely determine the lesion site.
Piccirilli	2000	Receptive + expressive	All of the results of neuropsychological assessments were within normal limits: memory, attention, visuospatial function, praxis, psychomotor integration, and intellectual processes.	Normal in intellect, language, memory, constructional ability, and frontal function.	No description of specific content of guitar performance.
Satoh	2005	Receptive + expressive	No aphasia, apraxia, dyscalculia, or visual discrimination difficulties were detected. Token test: 164/167.	Token test 164/167. Normal environmental sound recognition. No aphasia, apraxia, or amnesia.	Replacement of melody during the singing of familiar songs (paramelodia).
Terao	2006	Receptive + expressive	WAIS-R: VIQ 103, PIQ 98. Excellent memory for both verbal and non-verbal information.	WAIS-R: VIQ 103, PIQ 98. No aphasia, apraxia, or amnesia.	None.
Barquero	2010	Impairment of esthetic appreciation of music	The extensive neuropsychological examinations were normal.	Normal neurological and neuropsychological examination.	The patient also suffered from depression. The author judged that the symptoms were unrelated to depression.
Hochman	2014	Expressive (singing)	Without receptive or expressive aphasia, alexia, or agraphia.	Normal neurological examination without aphasia, alexia, or agraphia.	The close assessments of perception and expression of musical ability were not performed.

to examine cases with amusia [6,11], musical hallucination [16], callosal disconnection in a violinist [17], singing seizure [18], and musical anhedonia [9]. In this paragraph, I introduce two amusic cases and summarize principal findings related to their symptoms.

Case reports

Case 1: Pure amusia[11]

A 70-year-old right-handed woman had an episode of bilateral infarction of the temporal lobes 17 years prior to our study. Acutely, she suffered from right hemiparesis and aphasia, which disappeared after several months. Following her discharge, she found herself unable to recognize familiar music. The symptoms remained unchanged for 17 years, and her musical ability had never been tested.

On June 19, 1999, the patient developed a sudden mild right hemiparesis and was admitted to a hospital in Tokyo. No dementia, sensory disturbances, aphasia, apraxia, dyscalculia, or visual discrimination difficulties were detected. The pure-tone and speech audiometries were also within normal limits. No apparent deficit was detected in the patient's receptive and expressive speech, as assessed by two aphasic battery sub-tests; notably she obtained a normal score (164/167) on the Token test. The right hemiparesis disappeared in one week. Brain MRI confirmed the existence of bilateral temporal lobe lesions (Figure 2), and also revealed a small new infarction at the left coronal radiation. The patient was referred to me for assessment of her impairment in musical ability. Her musical background was that of a non-musician who enjoyed listening to popular and classical music, and regularly attended concerts before her illness. She met criteria for Grison's third level of musical culture [19]. She had completed 14 years of formal education and had suffered from

arrhythmia and hypertension for twenty years.

Her complaints about music were as follows: i) despite her former experience as a tango dancer, she could no longer distinguish tango from other types of music and she could identify tango music only by looking at a dancer's steps, ii) when she heard her recorded disc to which she had repeatedly listened, she felt as if she listened to the songs for the first time, and iii) she perceived her singing as out of tune when it was not.

Case 2: Auditory agnosia with impairment of perception and expression of music [6]

A 68-year-old right-handed businessman suffered from aphasia following an infarction in the left temporal lobe in 1989. The aphasia whose main symptom was anomia in his business situation disappeared in a few years and no neuropsychological deficit remained. On the morning of January 3, 1996, he found it hard to hear spoken language. He could hear voices on the television and telephone, but he could not understand what was said. He could speak fluently and write and read correctly. He had no weakness, no sensory disturbance, no apraxia, no dyscalculia, nor any visual discrimination difficulties. He consulted a hospital on January 24, and a brain MRI revealed a new infarction in the right temporal lobe (Figure 3). Pure tone audiometry revealed a slight deficit in the high frequency area that was within normal limits for his age. Speech audiometry revealed that the degree of maximal discrimination was only 50% in each ear. He had a low score (143/167) on the Token test, but, when questioned by written language, his score improved to 159. He also had a mild difficulty in understanding environmental sounds. His ability to hear spoken language improved gradually for a year. He was diagnosed with auditory agnosia (namely pure word deafness, environmental sound agnosia and receptive amusia) and expressive amusia.

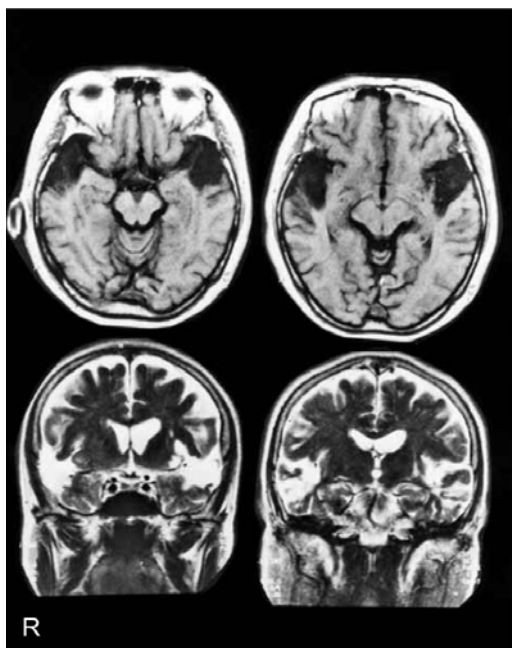


Figure 2: Brain MRI of Case 1. Brain MRI of the patient carried out 17 years after the onset of amusia. Upper and lower images show axial T1 and coronal T2 weighted images, respectively. Old infarcted lesions are observed bilaterally in the anterior portion of the temporal lobes including the temporal poles.



Figure 3: Brain MRI of Case 2. Axial MRI images of the patient carried out 2 years after the onset. Upper and lower images show the T1- and T2-weighted images, respectively. Old infarcted lesions are observed in bilateral temporal lobes more extensively on the right.

Table 2. Assessments of musical abilities*Perception of music*

Pitch discrimination (Hz)	After presenting a pure-tone of 440Hz as the standard, we presented a second tone and measured the range in which the standard and second tones were heard as the same pitch.
Discrimination and recognition of familiar songs (/30)	Thirty familiar nursery songs, all in a major key, were chosen and in twenty of these songs, part of the melody was locally altered. Two different response modes were used: (i) song decision; (ii) 'familiar-unfamiliar' decision.
Discrimination of unfamiliar phrases (/30)	The tonal memory test of Seashore's measures of musical talents [20] was used. Subjects were presented with 2 serial phrases and were asked which tone was altered in the second phrase.
Rhythm discrimination (/30)	The rhythm test from Seashore's measures of musical talents [20] was used. Thirty pairs of rhythm patterns were presented, and subjects were asked to make a same-different discrimination.
Meter discrimination (/4)	We used items from the meter test of a test for assessment of musical capacity for school children [21]. Following an example of 2 pieces of music that had double or triple time, the examiner presented 4 pieces of music that had double or triple time. The subject was then required to answer "two" or "three" for each piece of music.
Discrimination of isolated chords (/14)	A pair of chords in which the interval was 1 second was presented and subjects were asked to make a same-different discrimination. We used an item from the harmony test from a test for the assessment of musical capacity for school children [21].
Judgment of tonality (/20)	We made 20 kinds of sequences of 3 chords in which 2 chords had subdominant to dominant seventh progression. The last chords of 8 tasks were the tonic chords of each key which induced a natural feeling of an end. In 12 tasks, the last chords were irrelevant to the preceding 2 chords, which induced an unfinished, peculiar feeling. Subjects were asked to make a finished/unfinished response for each task.

Expression of music

Singing familiar songs	The patient and control subjects were asked to sing 10 well-known Japanese nursery songs without accompaniment with the help of written lyrics.
Reproduction of single sounds	Subjects were required to vocally reproduce single tones presented by the examiner. The examination was performed under 2 conditions: (i) while the tone was sounding, and (ii) immediately following the end of the tone presentation.
Reproduction of two-note phrases	Subjects were presented with 3 2-note phrases and were asked to sing each phrase. The phrases consisted of 2 notes whose pitches were separated by 3, 4 or 5 degrees (eg. D-F sharp, D-G, and D-A).
Reproduction of simple rhythm	Ten simple rhythm patterns 2 bars long in 4/4 time were presented and subjects were required to reproduce the rhythm by hand clapping.

In June 1999, he was referred to my laboratory because of his persistent complaints concerning the disturbance of perception and expression of music. He had never taken music lessons but enjoyed listening to recorded music and live concerts. He met the criteria for Grison’s third level of musical culture [19] and had suffered from arrhythmia for ten years.

His complaints about music processing were as follows: i) his singing became completely out of tune, ii) the music that he had enjoyed listening to before was wearisome and the esthetic pleasure was gone, iii) when he sang familiar songs with the accompaniment of *karaoke*, he could hear the accompaniment during the prelude, but as soon as he started to sing, he could not listen to the accompaniment completely, and iv) he could not understand spoken words when there was background music (BGM).

Results of neuromusiological assessments

In order to investigate the musical abilities of our patients, I carried out assessments of perception and expression of music, and performed statistical analysis of the results between my patients and controls. The contents of the assessments are shown in Table 2. Eight male and 4 female right-handed subjects with no history of neurological or psychiatric disease served as controls. Their ages ranged from 55 to 72 years (mean age 62 years). Control subjects were volunteers with musical background and education similar to those of my patients.

The results are shown in Table 3. Case 1 reported that she could not discriminate isolated chords because all of the chords sounded the same to her. The patient could correctly sing songs she knew well, such as “The Moon”. However, in singing less familiar songs, her singing was sometimes out of tune, though the rhythm and contour of the melody were preserved. When she sang an old Japanese tune in quadruple time (“I’m a Marine Child”), the third phrase of that melody was replaced with a phrase of a tune in triple time (“My Home Country”). When she sang “New Year’s Day”, the fourth phrase of that melody was replaced with the fourth phrase of another tune (“Urashima Taro”). The patient reported that such replacement of melody often occurred when she sang at home. Twenty minutes after this episode, she was able to sing these songs correctly. In the reproduction of two-note phrases, control subjects could discriminate and reproduce these two-note phrases easily, while patient 1 was unable to tell the difference between the phrases. She stated that all phrases sounded similar. Despite her inability to discriminate the phrases, she could correctly sing each phrase.

In case 2, the discrimination of isolated chords was compromised, but the judgment of tonality was the same as that of controls. The singing of case 2 was entirely out of tune, even of songs he knew well. The rhythm and the contour of the melody were mostly preserved. The pitch was severely impaired, as if frequent disordered transposition occurred. He was not aware of the inaccuracy of his own singing. Accompaniment by keyboard did not improve his performance. All control subjects could readily reproduce the single tone during and following termination of the tone presentation. Patient 2 could not reproduce a single sound presented by the examiner following the termination of tone presentation, in spite of his efforts over about ten minutes. He could not fix the pitch of tones, and he did not notice

this. In the reproduction during the tone presentation, he complained that he could not hear the sounding tone, and he could not judge whether his own singing was correct or not. Control subjects could discriminate and reproduce 3 simple phrases easily. Patient 2 could discriminate 3 simple phrases, but sang them entirely out of tune.

Discussion

Based on the results of cases 1 and 2, and of the literature covering case and my previous activation studies, I present the following aspects regarding the perception and expression of music.

Paramelodia

In neurocognitive science, it is generally accepted that memory consists of three steps: encoding, storage and retrieval. ‘Encoding’ is the uptake of the information into the brain, ‘storage’ concerns the keeping of information in the brain, and ‘retrieval (or recall)’ is the recollection of stored information when it is necessary. These steps can also be applied to music processing. For example, in singing, the information of the melody is retrieved, then it is changed into movements of the pharyngolarynx, and finally the song is uttered.

In case 1, the phrases of some melodies were replaced with those of other ones, while she sang well-known nursery songs. On another day, she could correctly sing these songs and it was supposed that the storage of these songs was preserved. Therefore, her symptoms of replacing melodies might be caused by a disturbance in the retrieval of melodies. Similar to paraphasia, which is the impairment of repeating words or sentences due to a retrieval dysfunction in aphasia, I named this symptom *paramelodia*. It is noteworthy that in *paramelodia*, the replacement of melodies occurred in a unit of four bars and one phrase. This fact suggests that the song is retrieved during singing by a unit of one phrase, and not in its entirety. We may say that singing familiar songs is based on a parallel processing of retrieval of phrases simultaneously while singing. The length of most modern folk and nursery songs in Western style is four, eight, twelve, or sixteen bars, and so on. Thus, “four bars” might be a fundamental unit of melodic organization, at least in Western music from about 1600 on.

How does *paramelodia* occur? The contours and times of replaced

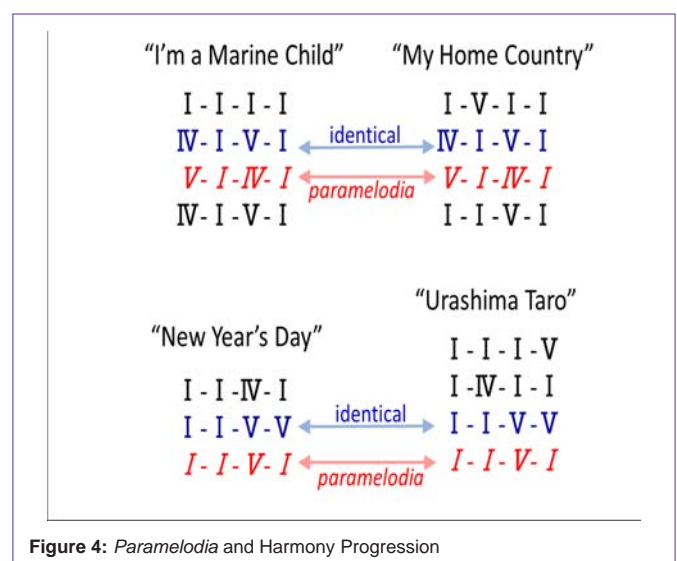


Figure 4: Paramelodia and Harmony Progression

Table 3. Assessments of musical abilities

		Case 1	Case 2	Control
<i>Perception of music</i>				
	Pitch discrimination (Hz)	429-442	438-446	434-446
	Discrimination and recognition of familiar songs (/30)	21***	21***	27.7 (26-30)
	Discrimination of unfamiliar phrases (/30)	3***	9***	21.8 (17-27)
	Rhythm discrimination (/30)	29	20	24.8 (20-29)
	Meter discrimination (/4)	3	3	3.8 (3-4)
	Discrimination of isolated chords (/14)	impossible	9**	12.6 (11-14)
	Judgment of tonality (/20)	14	13	15.6 (12-19)
<i>Expression of music</i>				
	Singing familiar songs	replace familiar melodies	out of tune	well
	Reproduction of single sounds	well	impossible	well
	Reproduction of 2-note	well	impossible	well
	Reproduction of simple rhythm	well	well	well
				*p<0.05 **p<0.01 ***p<0.001 (): range of the answers

melodies were quite different. I noted the particular similarity of the harmony progression of the preceding phrase of replaced melodies (Figure 4). Consequently, I may say that the *paramelodia* was caused by a similarity of the harmony of the preceding phrase. In other words, when we retrieve melody from memory storage, we may retrieve following phrases based on information related to the harmony progression of the preceding phrase. Further studies are needed to clarify the cognitive processing of the retrieval of a beginning phrase of a tune.

Conduction amusia

The mechanism of expressive amusia can be hypothesized according to two mechanisms. When a patient complains that he/she cannot sing well, it is possible that the patient has an impairment of the expressive system itself or a disconnection between the receptive and expressive systems related to music. An amateur accordion player reported by Botez [22] could not sing the same single tone presented on a keyboard, though he completely understood the incorrectness of his singing. He could correctly sing a scale and also perceive the pitch of a single tone. Therefore, it was supposed that his singing impairment was caused by an inability to utilize the pitch information of the perceived tone for his singing.

My case 2 could discriminate the pitch difference correctly and utter a voice at an arbitrary pitch. These facts demonstrate that his

ability to perceive and utter a single tone was preserved. However, he could not sing the same single tone presented by the examiner. So, I may reasonably conclude that the autoregulation of pitch control did not function because the perceived pitch information was not processed into singing. I named this symptom *conduction amusia*, meaning disconnection between the receptive and expressive systems of music processing. A case study that has an intact expressive system but cannot sing a single tone the same as the represented pitch would further clarify this type of disconnection.

Chord perception and anterior temporal lobes

Case 1 complained that a pair of chords sounded quite similar to her. From her case, I may say that the anterior portion of the temporal lobes plays some role in chord recognition.

I performed a PET activation study that recorded activated brain regions during chord and melody perception [23]. The subjects were young, right-handed non-musicians (age 20~30 years old). They listened to three newly composed musical pieces (C major, 24 bars, three vocal parts) in the following two ways: i) a harmony listening task, and ii) a soprano listening task. During the task performances, I measured regional cerebral blood flow (rCBF) using PET and identified the brain regions that activated in each task. As a result, during the harmony listening task, the anterior portion of the bilateral temporal lobes, cingulate gyri, and cerebellum were

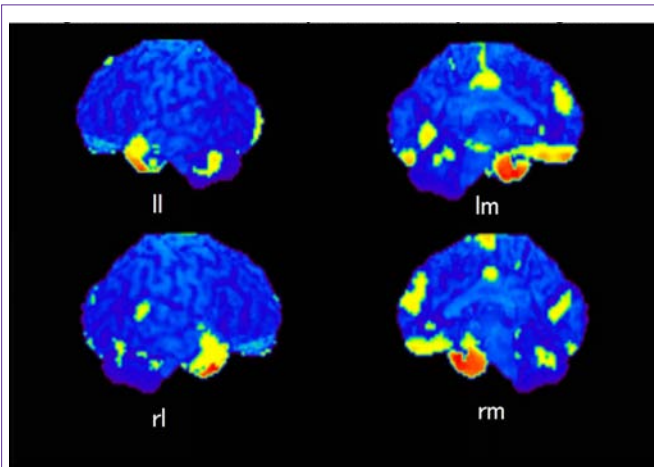


Figure 5: PET Activation Study after Harmony-Listening Task. Activation maps for comparison of the harmony-listening versus the soprano-listening tasks. Areas of significant activation ($p < 0.01$) are superimposed onto the surface maps of the averaged MR imaging. Anterior portions of the bilateral temporal lobes are activated. ll: lateral surface of left hemisphere, lm: medial surface of left hemisphere, rl: lateral surface of right hemisphere, rm: medial surface of right hemisphere.

activated, compared to the soprano listening task (Figure 5).

The results of our case 1 and a PET activation study can be summarized as follows: the recognition of chords was impaired in a case of pure amusia with lesions of the anterior portion of the bilateral temporal lobes and, in a PET study, the same brain regions were activated during a harmony listening task. Therefore, I may say that the anterior temporal lobes participate in the recognition of chords.

Karaoke and a cappella

Most songs consist of a melody and an accompaniment. The term *karaoke* refers to singing with automated accompaniment. When we sing correctly in *karaoke*, it is necessary not only to sing melodies in correct pitches, rhythms, and tempo, but also to listen to accompaniments and regulate our own singing, keeping harmony with the accompaniment. After the cerebrovascular accident, the performance of singing with karaoke became worse in case 2 and the patient complained that the accompaniment could not be heard as soon as he started to sing. This phenomenon was different from the situation in which he could listen to the accompaniment and could not keep in harmony with it. This symptom might be caused by a decrease in cognitive volume of the information that he could deal with simultaneously.

The problem of figure-ground segregation in human cognition has been extensively studied in the field of vision research. A similar condition in audition is known as the cocktail party effect. Even in a noisy situation such as a cocktail party, we can notice when our own names are called or we can listen to selective speeches in the conversation. It is generally accepted that auditory attention participates in the cocktail party effect, but its mechanism and associated brain regions are still uncertain. The findings from case 2 might provide some clues to this mystery.

Tonality

Most music to which we usually listen is based on tonality.

Tonality is a term to denote the series of relationships between pitches in which one particular pitch, the 'tonic', is central [24]. It takes in the term 'key' but also has wide implications, especially concerning the functional association of other notes and chords with the tonic. So, the tonality cannot exist by a single tone or chord, but is built on the relationship between multiple tones and chords. In other words, the melody and harmony progression are necessary to produce the tonality. Then, is the tonality a derivative product based on the perception of melody and harmony? Or, is it an independent component in the perception of music? Peretz reported a patient with an impairment in the perception of tonality, and concluded that the tonality could be an independent component in the perception of music [15]. The patient exhibited a preserved ability in melody and harmony perception, but she could not perceive tonality. The findings of my case 2 displayed a preservation of tonality, though the perception of the melody and chords was impaired. The results of case 2 were strange. It was supposed that the judgment of end perception based on the progression of three chords was more difficult from the discrimination between a pair of isolated chords. Regarding the perception of tonality, a double dissociation was observed between the results of Peretz's and my case 2: the case of Peretz showed a preserved melody and harmony and impaired tonality, and my case revealed the counter pattern. From these results, I can reasonably conclude that tonality is an independent component of music perception.

Diagram of the perception and expression of music (Figure 6)

Based on findings from the reported literature and in my patients, I constructed a diagram concerning the mechanisms related to the perception and expression of music, though much still remains to be clarified.

Perception of music- The dissociation between the perception of rhythm and pitch reveals that rhythm and pitch are perceived by different processes. My cases showed a double dissociation with the case of amusia due to rhythm agnosia reported by Mavlov [13]. At the first stage, when we listen to music, the melody is perceived as divided into pitch and rhythm. These two components that had been subdivided are then integrated again and form the receptive melody-image, meaning the representation of internal imagery [25] of the melody. The receptive melody-image includes the short term or working memory (STM) of melody. When asked to discriminate the two phrases, the receptive melody-image of the former phrase is compared with the latter phrase in the receptive melody-image. The comparison between the receptive melody-image and the memory is thought to be impaired in both patients. Harmony is defined as the combining of notes simultaneously, to produce chords [24]. Takeuchi suggested that there was a difference in mechanisms between the perception of a single tone and of the pitch-interval, presumably related to the pitch and the harmony [26]. The tune is usually composed of the melody and the accompaniment. While listening to music with the accompaniment, information about the rhythm and pitch of the tune form not only the receptive melody-image but also the image of the accompaniment. When asked to judge the suitability between the melody and its accompaniment, the receptive melody-image is compared with the image of the accompaniment. This process might be dysregulated in case 2. The harmony and the

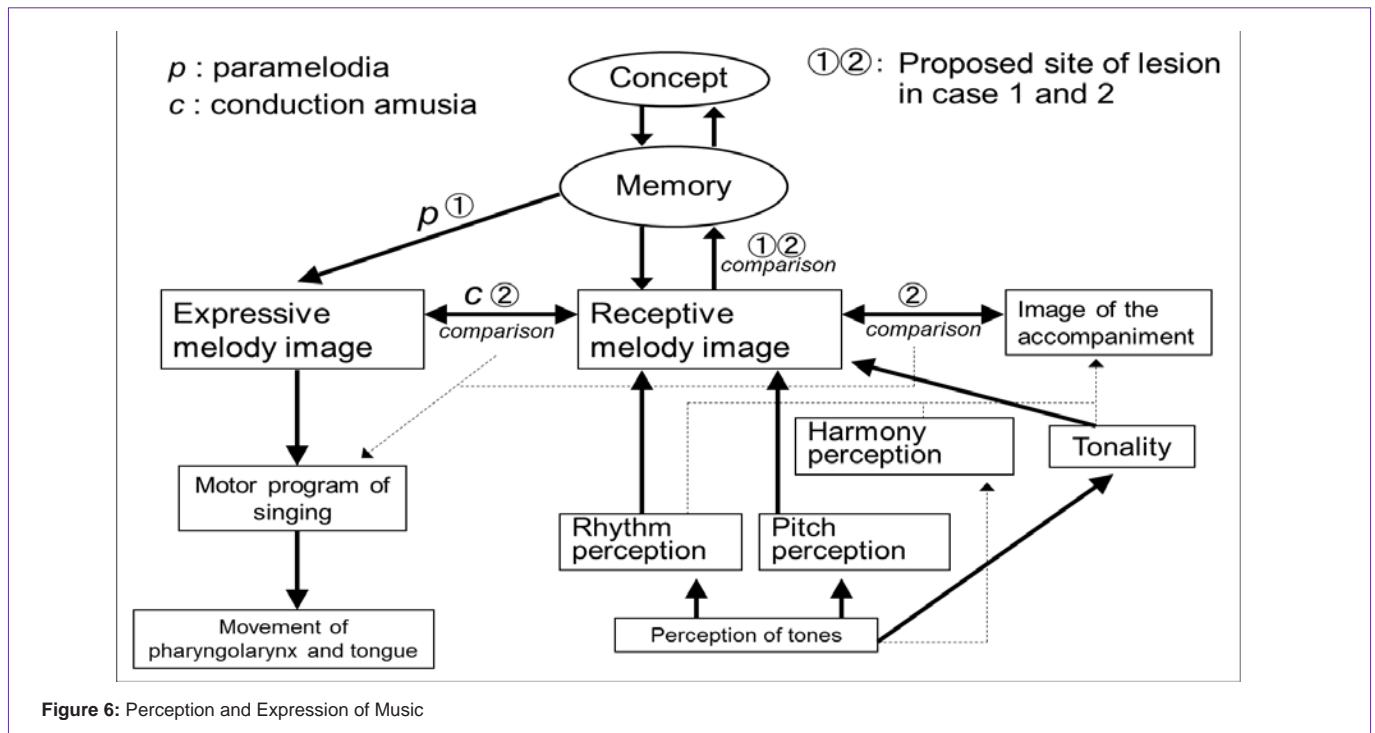


Figure 6: Perception and Expression of Music

tonality are also independent components of music perception and related to the formation of the image of the accompaniment.

Expression of music- When we sing a familiar song, the melody is retrieved from memory by a unit of four bars and forms the expressive melody-image, as shown in our study. Dysfunction of this retrieval produces *paramelodia*, as in case 1. While singing, self-regulation is performed by making a comparison between the expressive melody-image and the receptive melody-image. This comparison is hypothesized to be impaired in case 2. The results of this comparison and the comparison between the receptive melody-image and the image of the accompaniment modulate the motor-program for singing. When asked to sing a melody or a phrase to which the subject is listening for the first time, the melody or phrase information is connected to the expressive melody-image from the receptive melody-image. The connection from the receptive to the expressive system might be dysfunctional in case 2. The expressive melody-image connects to the motor-program for singing and, finally, produces the movements of the pharyngolarynx and tongue, that is, “singing”.

Conclusion

The perception and expression of music has long been considered by philosophy and musicology. Now, we possess innovative tools for functional activation studies, while the importance of case studies in driving cognitive neuroscience has become much greater than ever. I can say that, with the delay of one and a half century, the research of cognitive processing of music is going to approximate to that of language.

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