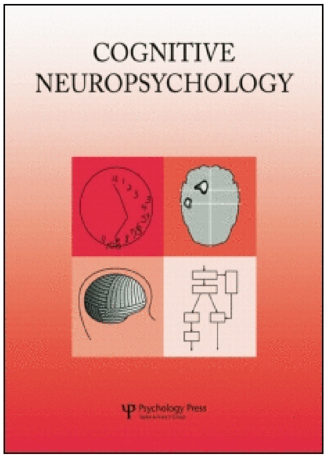

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Harmonic priming in an amusic patient: The power of implicit tasks

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Harmonic priming in an amusic patient: The power of implicit tasks

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Our study investigated with an implicit method (i.e., priming paradigm) whether I.R.—a brain-damaged patient exhibiting severe amusia—processes implicitly musical structures. The task consisted in identifying one of two phonemes (Experiment 1) or timbres (Experiment 2) on the last chord of eight-chord sequences (i.e., target). The targets were harmonically related or less related to the prior chords. I.R. displayed harmonic priming effects: Phoneme and timbre identification was faster for related than for less related targets (Experiments 1 and 2). However, I.R.'s explicit judgements of completion for the same sequences did not differ between related and less related contexts (Experiment 3). Her impaired performance in explicit judgements was not due to general difficulties with task demands since she performed like controls for completion judgements on spoken sentences (Experiment 4). The findings indicate that implicit knowledge of musical structures might remain intact and accessible, even when explicit judgements and overt recognition have been lost.

The dissociation between implicit and explicit task performance has been reported in various neurological disorders (e.g., alexia, agraphia, aphasia, prosopagnosia). Indirect investigation methods have provided evidence for the influence of spared implicit knowledge on perception and action in the presence of severe impairments in tasks requiring explicit processing. A well-known example is the condition of "blindsight" in which patients can indicate the location of a visual object and estimate its size, while denying its conscious perception (Weiskrantz, 1986). Another

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Examples for materials of Experiments 1 to 4 are available at: http://olfac.univ-lyon1.fr/bt-sound.html. This research was supported in part by the CNRS programme "Cognition and Information Processing", the grant "ACI Junior Research Team" by the French Ministry of Research, and grants from the Canadian Institute for Health Research and the Canadian Natural Science and Engineering Research Council.

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example is the observation that amnesic patients show implicit memory of recent events despite lack of explicit memory (Schacter & Buckner, 1998).

Implicit knowledge and memory refer to stored information and its recollection in the absence of awareness. It is said to be nonconscious and stands in contrast to explicit knowledge, which can be consciously recollected and verbalized.[1] Implicit knowledge is supposed to involve neurological substrates that are more resistant to neurological attacks than are those of explicit knowledge (Reber, 1992). Implicit processes are revealed by experimental methods that are drawing the perceivers' attention to features of the stimulus other than those being assessed. For example, in the priming paradigm, the processing of an event can be influenced by prior exposure to either itself (repetition or sensory priming) or a related event (cognitive priming). The basic set-up consists of a prime context followed by the to-be-processed target event that is either the same or related (i.e., relations concerning semantics, familiarity, or harmony). The central feature of this paradigm is that participants are not required to make direct judgements on the relation between prime and target, but their task focuses on a perceptual or conceptual feature of the target that is manipulated independently of the relations under study.

Priming experiments have provided evidence for spared implicit processes despite impaired explicit functions. For example, a patient with nonfluent aphasia showed semantic priming in a lexical-decision task despite severe deficits in semantic matching of words to pictures (Mimura, Goodglass, & Milberg, 1996). A patient with prosopagnosia has been unable to explicitly recognize a face but the familiarity of the face influenced the processing of a word presented thereafter (Young, Hellawell, & DeHaan, 1988). Until now, a dissociation between implicit and explicit processes in brain-damaged patients has not been documented in music cognition (but see Peretz, Belleville, & Fontaine, 1997, for one attempt). The goal of our study was to assess whether an amusic patient would exhibit implicit processing of harmonic relations in a priming experiment.

The harmonic priming paradigm, as applied to healthy listeners, is a well-established tool for revealing that listeners without formal musical training have acquired implicit knowledge of tonal harmony, by mere exposure to music in everyday life (Bigand & Poulin-Charronnat, 2006; Tillmann, Bharucha, & Bigand, 2000). Harmony refers to structural regularities between chords (i.e., three or more tones sounding simultaneously) in Western tonal music. A hierarchy of functional importance exists between chords: The tonic chord is at the top of the hierarchy and represents the most referential event of a key; it is followed by the dominant chord, the subdominant chord, other in-key chords, and finally out-of-key chords. Harmonic priming data confirmed and extended evidence for listeners' sensitivity to harmonic functions and relations between chords. This sensitivity has been also investigated with explicit methods, such as subjective judgements of completion (Bigand & Pineau, 1997), musical tension (Bigand, Parncutt, & Lerdahl, 1996), and similarity (Bharucha & Krumhansl, 1983; Krumhansl, Bharucha, & Kessler, 1982). In the harmonic priming paradigm, the relations between the prime context (e.g., a chord sequence) and the target (e.g., a chord) are manipulated on the basis of harmonic relations defined by music theory. This relatedness manipulation uses the

[1] Explicit knowledge and processes have been associated with consciousness and verbalization and are considered to form the contents of phenomenal experience, while implicit knowledge and processes have been associated with unconsciousness (Dienes & Perner, 1999, 2003) and are considered as not being part of the unity of consciousness (Cleeremans, 2003; Cleeremans & Jimenez, 2002 for a graded perspective of consciousness). It has also been argued that, for example, the blindsight phenomenon does not refer to implicit, unconscious perception, but is rather based on states of phenomenological consciousness that are altered for these patients in comparison to healthy individuals (Perruchet & Vinter, 2002). A full account of the explicit/implicit distinction and its relation to consciousness is, however, beyond the aim of the present article.

context dependency of musical events: The same chord can be strongly related, less related, or unrelated to the preceding harmonic context. Participants make speeded judgements on a perceptual feature of the target chord—for example, sensory consonance/dissonance judgements (e.g., Bharucha & Stoeckig, 1986; Bigand & Pineau, 1997), timbre identification (Tillmann, Bigand, Escoffier, & Lalitte, 2006a), or phoneme identification in sung music (Bigand, Tillmann, Poulin, D'Adamo, & Madurell, 2001). These various tasks have provided evidence for the influence of harmonic relations on the speed of musical event processing: Target chords are processed faster after harmonically related contexts than after unrelated, out-of-key contexts (Bharucha & Stoeckig, 1987; Tillmann, Bigand, & Pineau, 1998) and even after less related contexts (Bigand, Madurell, Tillmann, & Pineau, 1999; Bigand & Pineau, 1997; Bigand et al., 2001). These latter findings point out that listeners perceive tonal differences between in-key events. Cognitive priming (based on listeners' knowledge about possible relations between chords) prevails over sensory priming (based on the acoustic overlap between prime and target): Processing of related targets is facilitated even when less related targets share more tones with the context than do related targets (Bigand, Poulin, Tillmann, & D'Adamo, 2003; Tekman & Bharucha, 1998) and when the preceding chord is acoustically the same as the target (Bigand, Tillmann, Poulin-Charronnat, & Manderlier, 2005). The present study focuses on cognitive priming because the amusic patient I.R. has perceptual deficits in music processing, but may nevertheless have spared musical knowledge.

I.R. has been extensively studied (Belleville, Caza, & Peretz, 2003; Griffiths et al., 2000; Patel, Peretz, Tramo, & Labreque, 1998b; Peretz et al., 1997; Peretz, Blood, Penhune, & Zatorre, 2001; Peretz & Gagnon, 1999; Peretz, Gagnon, & Bouchard, 1998). She represents a remarkable case because 20 years after the brain damage she still experiences severe difficulties with music, while basic auditory functions, language abilities, as well as general intellectual and memory abilities are normal. I.R. can no longer sing, recognize, or memorize music; she fails in various melodic and temporal tests requiring direct judgements. These explicit tests have used melodic material (e.g., Peretz et al., 1997) or melodies with harmonic accompaniment (Peretz et al., 2001; Peretz et al., 1998). The present study uses chord sequences and tests I.R. with both implicit and explicit investigation methods. Experiments 1 and 2 use priming tasks based on phoneme and timbre identification, respectively. Experiments 3 and 4 use explicit judgements of completion on the same musical material as that in Experiment 2 and on spoken sentences as a control condition. Based on her previous data, I.R.'s explicit completion judgements should not differ between related and less related chord sequences. However, based on previously reported neuropsychological cases in other domains, our hypothesis is that the priming paradigm might allow implicit access to eventually spared musical knowledge in I.R. and reveal processing differences between related and less related target chords.

EXPERIMENT 1: HARMONIC PRIMING WITH A PHONEME IDENTIFICATION TASK

In Experiment 1, I.R. and four matched controls were tested with a priming paradigm using eight-chord sequences, each chord consisting of four voices singing a consonant–vowel (CV) syllable (Bigand et al., 2001). The target, corresponding to the last chord of a sequence, was either related to the prime context (i.e., the first seven chords) and strongly expected (it functioned as the tonic chord) or less related and less expected (it functioned as the subdominant chord). Participants had to identify as quickly as possible whether the target was sung on /di/ or /du/. To focus on cognitive priming, neither related nor less related targets occurred in the prime context. On the basis of listeners' knowledge about musical structures, related targets should be more strongly expected, which should lead to facilitated processing. In Bigand et al.'s (2001) study, phoneme identification was faster when the phoneme was sung on related than on less related target chords. For I.R., the phoneme identification task seemed particularly adequate since I.R. has no problem with speech perception. If some implicit musical knowledge is spared in I.R., her response pattern should show facilitated processing for related tonic targets over less related subdominant targets.

Method

Participants

I.R. is a right-handed woman, with 10 years of education, who was 48 years old at the time of testing. I.R.'s latest assessment with the Wechsler Adult Intelligence Scale–Revised (WAIS–R) indicates a normal intelligence for her education and a normal memory functioning, with the exception of an impaired short-term memory (STM; Belleville et al., 2003). The musical context effect requires STM to some extent because musical relatedness arises from the tonality instilled by the overall sequence. However, the tasks did not require explicitly comparing two items in contrast to most STM tasks (i.e., same/different judgements). I.R. exhibits normal scores on language comprehension and discrimination tests (see Table 1; see Peretz et al., 1997, for more details and Patel et al., 1998b, for an examination of prosodic aspects). She is musically untrained although she was musically inclined and grew up in a musical environment (her only brother is a professional musician). Normal audiometry indicates normal auditory acuity.

I.R.'s lesions (see Figure 1) include all or most of the superior temporal gyrus (STG) in the left hemisphere. Heschl's gyrus and the anterior portion of the planum temporale (PT) have been completely destroyed (see Griffiths et al., 2000, for further information). The temporal lobe lesion extends inferiorly into the middle temporal gyrus, superiorly into the parietal operculum (supramarginal gyrus), and anteriorly into the pre- and postcentral gyri and also destroys the posterior half of the insula. In the right hemisphere, the temporal lobe damage appears to be confined to the most anterior and superior portion of the STG near the pole. Heschl's gyrus is entirely

Table 1. *I.R.'s performance on tests of intelligence, memory, and audition (language and music) and averaged percentages of correct responses of four matched controls for nonstandardized tests*

Test		*I.R.*	*Matched controls*
Intelligence	WAIS–R	94	—
Memory	WAIS–R	99	—
Audition	Audiometry	normal	
Language	Token test	56/62	—
	Auditory lexical decision	77/80	—
	Word discrimination	36/36	—
MBEA[a]	Scale	15/30 (50.0)	85 (21, 29)
	Contour	15/30 (50.0)	88.3 (23, 29)
	Interval	15/30 (50.0)	83.3 (20, 30)
	Rhythm	15/30 (50.0)	92.5 (25, 30)
	Meter	20/30 (66.7)	84.17 (19, 30)
	Recognition memory	15/30 (50.0)	76.67 (20, 25)
	Tonal closure[b]	19/30 (63.3)	91.0 (25, 29)

Note: The control data come from Peretz, Belleville, and Fontaine (1997). Values shown are averaged percentages, with lowest and highest scores in parentheses. WAIS-R = Wechsler Adult Intelligence Scale–Revised. MQ = memory quotient. MBEA = Montréal Battery of Evaluation of Amusia.
[a]Percentages shown in parentheses. Chance level is 50%. [b]I.R. was asked to judge the adequacy of the final tone, notably whether the melody sounded complete or incomplete (with a yes–no response choice).

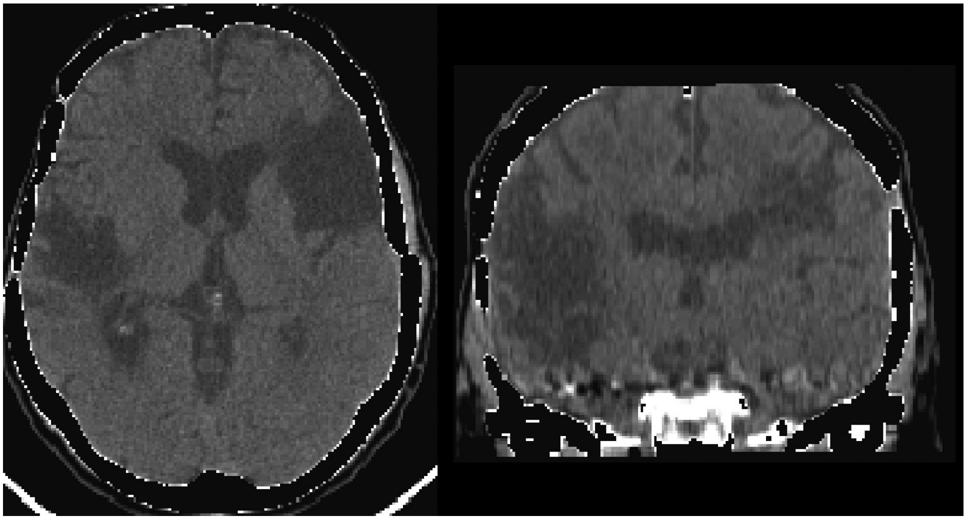


Figure 1. *Axial (z = 7) and coronal (y = −15) slices of I.R.'s computed tomography (CT) scan (in MNI space) presenting temporal and frontal lobe damage in left and right hemisphere (see text for details). The right side of the image corresponds to the right side of the brain. Adapted from "Cortical deafness to dissonance", by I. Peretz, A. J. Blood, V. Penhune, & R. Zatorre, 2001,* Brain, 124, *p. 931, Figure 2, Copyright 2001 by Oxford University Press. Adapted with permission.*

spared, as is the PT behind it. In this hemisphere, the anterior portion of the insula is infracted, and the lesion encroaches medially into a small portion of the putamen. There is also a large frontal lobe lesion, including most of the precentral and inferior frontal gyri, as well as the white matter underlying them. Damage also encroaches on small regions of the lateral orbito-frontal and middle frontal gyri.

Normal scores are provided by four neurologically intact women, whose ages and socio-economic backgrounds closely matched those of I.R. (age mean: 46.3 yrs; education mean: 11.5 yrs; all are right-handed and nonmusicians). On the Montréal Battery of Evaluation of Amusia (MBEA, Peretz, Champod, & Hyde, 2003), three matched controls scored normally while one control (L.B.) performed just below the cut-off score of 22 that corresponds to two standard deviations below the mean of 160 unselected neurologically intact adults (see Peretz et al., 2003, for further details and Table 1 for the scores). Since L.B.'s data pattern in Experiment 1 was similar to that of the other matched controls, L.B. was kept as a control participant. The MBEA involves six subtests that aim to assess the various components that are known to contribute to melody processing. The stimuli are novel melodic sequences, played one note at a time on a piano; they are written in accordance with the rules of the tonal structure of the Western idiom. The sequences are four bars long, last about 4 s, and contain from 8 to 19 tones (mean: 10.7). These melodies are arranged in various tests so as to assess abilities to discriminate pitch and rhythmic variations and to recognize musical sequences heard in prior tests of the battery. The data pattern of L.B. on chord sequences (particularly in Experiments 1 and 3) suggests the need for future improvements of the MBEA, notably by including harmonic material in addition to the currently tested melodic material (as proposed by Peretz et al., 2003, and currently under development as announced in Sloboda, Wise, & Peretz, 2005). All participants gave informed consent on this project, which was approved by the ethical committee of the Institut Universitaire de Gériatrie de Montréal.

I.R.'s musical deficit has been characterized over the years, and only those aspects of her condition most relevant to the present study are summarized here (Table 1). On the pitch dimension, with which we are concerned in the present study, I.R. has difficulties. For example, she performs at chance on the "scale subtest" of the MBEA. This task requires the discrimination of a melody that contains an out-of-key tone. She is similarly impaired when asked to judge whether the final tone of a melody is an adequate closure. These impairments extend to multivoice music (Peretz et al., 1998). I.R. fails to detect local pitch shifts that create dissonance. This pattern cannot be explained by a simple defect in pitch discrimination since I.R. is able to identify as "same" or "different" isolated tones across varying pitch distances and complexity (Peretz et al., 2001). It is the quality of the pitch relations (i.e., involving consonance, intervals, pitch direction) and/or the task demands that seem to matter.

Materials

The material of Bigand et al. (2001) was used. It comprised 12 eight-chord sequences (covering the 12 major keys) ending on the related tonic and 12 sequences ending on the less related subdominant. The sequences were based on six-chord sequences completed with two-chord endings, constructed in such a way that the last chord (the target) functioned either as a tonic or as a subdominant (Figure 2). Each prime chord sounded for 625 ms, the target sounded for 1,400 ms, and the interchord interval was set to 0 ms. Sequences were played with sampled voice sounds of VokalWriter software. For prime contexts, 22 CV syllables were used together without forming meaningful, linguistic phrases (e.g., /da fei ku ʃo fa to kei/). The syllables /di/ and /du/ were always assigned to the target. Crossing relatedness (related vs. less related) and target type (/di/ vs /du/) resulted in 48 sequences. The experimental session thus consisted of 50% of sequences ending on the related tonic target (25% being sung with /di/, 25% with /du/) and 50% ending on the less related subdominant target (25% with /di/, 25% with /du/). The experiment was run on Psyscope software (Cohen, MacWhinney, Flatt, & Provost, 1993).

Figure 2. *Two eight-chord sequences illustrating the context effect: The same final chord (the target) functions as a related tonic chord in Sequence A, and as a less related subdominant chord in Sequence B.*

Procedure

Participants were asked to decide as quickly and accurately as possible whether the last chord of each sequence was sung on /di/ or /du/ by pressing one of two keys. Incorrect responses were accompanied by a feedback signal, and correct responses stopped the sounding of the target. A short random tone sequence was presented after each response to empty the sensory memory buffer and to avoid eventual carry-over effects from one sequence to the next. After 4 practice sequences, the 48 sequences were presented in random order twice in two blocks separated by a short break. For I.R., the first block was discarded because of a too severe response time limit leading to the failure of recording responses, and an additional (third) block was run.

Results

Accuracy was high for both I.R. (96%) and matched controls (98%). Because of differences in average response speed between participants (ranging from 520 ms to 1,499 ms) and with the goal to focus on differences between related and less related sequences, correct response times were individually normalized to z-scores with a mean of 0 and a standard deviation of 1 (Figure 3). Z-scores were averaged over the two blocks and were analysed with 2×2 analyses of variance (ANOVAs) with relatedness and target type as within-subject factors and sequences as random factor.

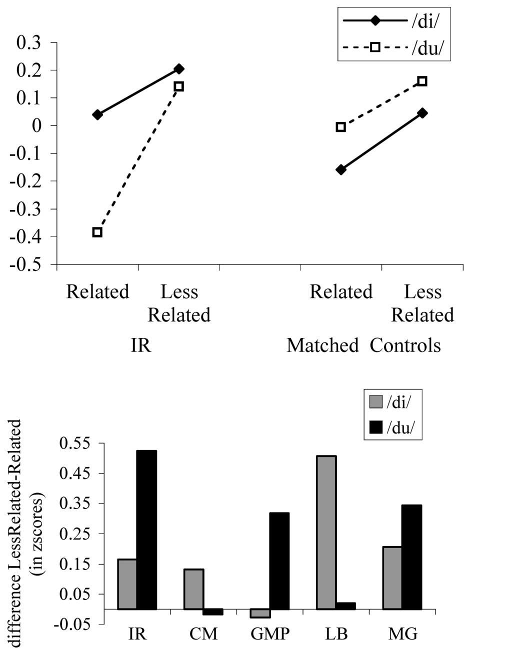


Figure 3. *Top: Correct response times (normalized to z-scores) of Experiment 1 presented as a function of musical relatedness (related/less related) and target phoneme (/di/ and /du/) for I.R. and the group of matched controls. Bottom: For matched controls, individual differences in response times (normalized to z-scores) between related and less related contexts presented for both target phonemes.*

I.R.

For I.R., the main effect of relatedness failed to reach significance; $F_2(1, 11) = 3.87$, $p = .075$. Since I.R. was performing three blocks (with the first one being discarded because of the failure to record responses), we were interested to assess whether the relatedness effect had been weakened by repetition. An analysis considering the two blocks (for which response times were recorded) as within-subject factor revealed a marginally significant three-way interaction between block (second/third), relatedness, and target type, $F_2(1, 7) = 3.98$, $p = .087$. For the second block only, the main effect of relatedness was significant, $F_2(1, 9) = 6.21$, $p < .05$, and tended to interact with target type, $F_2(1, 9) = 4.83$, $p = .056$: The relatedness effect was stronger for /du/ ($p < .01$) than /di/ (ns). This additional analysis revealed I.R.'s sensitivity to tonal relatedness, which was present in the second block, but decreased in the third block. Because of the missing data in the first block, we cannot conclude a constantly decreasing sensitivity. However, the absence of a block effect in Experiment 2 (opposing Block 1 to Block 2) suggests that the present decrease was limited to the third block of Experiment 1.

Matched controls

For matched controls, the main effect of relatedness was marginally significant, $F_2(1, 11) = 4.25$, $p = .06$. In the analyses of the data of each participant with items as the random factor, there were no significant effects. However, for each participant the mean differences indicated faster processing for related targets, at least for one of the target phonemes (see Figure 3, bottom). Differences between target types might be linked to individual response strategies, with one target being taken as the to-be-detected reference element and thus becoming less integrated to the context (see Tillmann et al., 2006a, for a similar rational on the timbre identification task).

Discussion

A harmonic priming effect was observed for the amusic patient I.R. in Experiment 1: Phoneme identification was faster when the phoneme was sung on a related tonic chord than when it was sung on a less related subdominant chord. Since the experimental task does not require paying attention to the music, the finding suggests that I.R. was automatically processing the musical relationships between the target chord and the preceding context. This finding suggests that some knowledge of Western tonal music is preserved in I.R. and continues to influence her musical perception at an implicit level. Experiment 2 investigated whether the influence of musical context extends to the processing of a feature that is not speech based.

EXPERIMENT 2: HARMONIC PRIMING WITH A TIMBRE IDENTIFICATION TASK

The most frequently used task in harmonic priming studies is based on consonance/dissonance judgements (e.g., Bharucha & Stoeckig, 1986; Bigand & Pineau, 1997). However, this task was not adequate for I.R. because she does not perceive sensory dissonance (Brattico, Tervaniemi, Valimaki, VanZuijen, & Peretz, 2003; Peretz et al., 2001). Experiment 2 used a more recently introduced musical timbre identification task that had replicated the harmonic priming effect (Tillmann et al., 2006a). In this task, the prime context is played with one musical timbre (i.e., Timbre A) and the target with either Timbre A or Timbre B. Participants make speeded timbre identification judgements on the target. The results show that timbre identification is faster for related than for less related targets. This harmonic relatedness effect is more pronounced for Timbre A than Timbre B because Timbre A creates a coherent, continuous sequence (i.e., with the prime context being played by the same timbre). Here, we used this version of the timbre identification task because the continuous sequences (i.e., entirely played by Timbre A) are the closest to natural listening situations of instrumental music and allow us to evaluate the processing of tonal relatedness without influences due to timbre changes. Based on the data of Experiment 1, we expected harmonic priming to occur for I.R. with this timbre identification task and particularly for Timbre A trials.

Method

Participants
I.R. and her matched controls participated in Experiment 2.

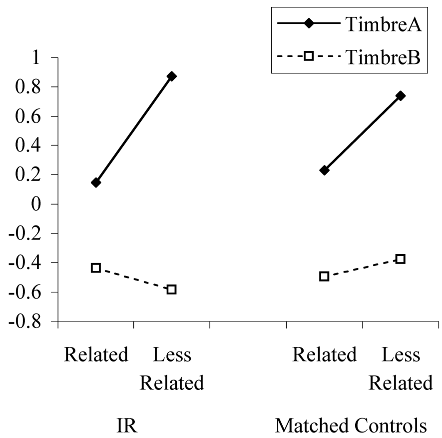
Materials
The material from Tillmann et al. (2006a) was used; it was based on the eight-chord sequences of Bigand et al. (2001), but played with musical timbres. The first seven chords were played with an acoustic piano sound (Timbre A) and the target with either this same acoustic piano sound (Timbre A) or with a harp sound (Timbre B). Each prime chord sounded for 620 ms, the target sounded for 2,000 ms, and the interchord interval was set to 0 ms. Presenting the 24 experimental sequences (12 related, 12 less related) with Timbre A and Timbre B resulted in 48 sequences. The experiment was run on PsyScope Software (Cohen et al., 1993).

Procedure
Participants were first trained to differentiate the two timbres with 24 single chords and 4 chord sequences. They were asked to judge as quickly and accurately as possible whether the isolated chord or the last chord of the sequence was played by Timbre A or B by pressing one of two keys. Timbre A was defined as sounding "bright" and Timbre B as "dull". For the sequences, participants were informed that the first 7 chords were always played with Timbre A. The 48 sequences were presented in random order twice in two blocks separated by a short break. An incorrect response was accompanied by an alerting feedback signal, and a correct response stopped the sounding of the target. The target was followed by a 250-ms noise mask, and the next trial started when participants pressed the space bar.

Results

As in Experiment 1, correct response times (ranging from 823 ms to 1,309 ms) were individually normalized to z-scores (Figure 4). Z-scores were averaged over the two blocks and were analysed with 2 × 2 ANOVAs with relatedness and target type as within-subject factors and sequences as random factor.

I.R.
I.R. showed no difficulties identifying the timbres (92%). For response times, the main effect of relatedness failed to reach significance, $F_2(1, 11) = 3.59$, $p = .08$, but relatedness interacted significantly with target type, $F_2(1, 11) = 8.52$, $p < .05$. Planned



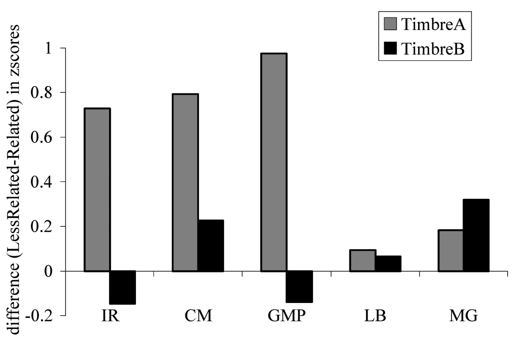


Figure 4. *Top: Correct response times (normalized to z-scores) of Experiment 2 presented as a function of musical relatedness (related/less related) and target timbre (A and B) for I.R. and the group of matched controls. Bottom: For matched controls, individual differences in response times (normalized to z-scores) between related and less related contexts presented for both target timbres.*

comparisons indicated that only for Timbre A were response times shorter for related than for less related targets, $F_2(1, 11) = 23.57$, $p < .001$. In addition, response times were faster for Timbre B than Timbre A, $F_2(1, 11) = 37.95$, $p < .001$. A second analysis considering block (first/second) did not reveal an influence of block on the response time pattern.

Matched controls

Accuracy was high for C.M. (95%), G.M.P. (97%), and M.G. (98%), but low for L.B. (41%). For response times, the main effects of relatedness, $F_2(1, 11) = 12.09$, $p < .01$, and of target type, $F_2(1, 11) = 76.41$, $p < .0001$, were significant: Response times were faster for related targets than for less related targets and faster for Timbre B than Timbre A. The two-way interaction between relatedness and target type was marginally significant, $F_2(1, 11) = 4.65$, $p = .05$: The relatedness effect was significant for Timbre A, $F(1, 11) = 10.00$, $p < .01$, but not for Timbre B ($p = .20$). In the analyses of each participant's data with items as random factor (except for L.B. because of missing values due to the low accuracy score), the main effects of relatedness and target type were significant (ps $< .05$). The interaction reached significance only for G.M.P ($p < .05$).

Discussion

Experiment 2 using timbre sequences replicated the harmonic priming effect observed in Experiment 1 with sung syllabic sequences. Even without the link to language processing, I.R.'s data pattern for Timbre A trials showed facilitated processing for related targets in comparison to less related targets. Like students (Tillmann et al., 2006a) and matched controls, I.R. was sensitive to the harmonic structures and developed musical expectations influencing timbre processing. I.R.'s data further showed her sensitivity to contexts ending on a timbre that was either the same or different from the context timbre: Response times were overall faster for Timbre B, and the priming effect was observed for Timbre A. This outcome is in agreement with the previously reported stronger context effect for Timbre A, notably because of its acoustic continuation with the prime context, which was also played with Timbre A (see Tillmann et al., 2006a, for further discussion). For Timbre B trials, the context effect was marginally significant in students (Tillmann et al., 2006a, Exp. 1) and not significant in matched controls and I.R. The different priming effects for Timbre A and Timbre B targets are related not to the timbral characteristics (i.e., piano vs. harp timbre), but to their association with the timbre of the prime context, which was either the same (i.e., Timbre

A, creating a continuously sounding sequence) or different (i.e., Timbre B). For Timbre B trials, the timbral change between prime context and target might disrupt the influence of the context as Timbre B targets are less well integrated into the overall sequence. Changes in the harmonic spectrum of sounds can function to segregate an event from a current auditory stream (Bregman, 1990), and this separation might account for the diminished impact of tonal context on target chord processing.

I.R.'s spared performance in harmonic priming tasks, which was comparable to that of healthy controls, stands in contrast to her prior failures with melodic material (Peretz et al., 1997) and melodies with harmonic accompaniment (Peretz et al., 2001; Peretz et al., 1998). Experiment 3 tested to what extent I.R.'s data pattern was due to the difference in investigation methods (explicit vs. implicit). The harmonic material of Experiment 2 (chord sequences played entirely with Timbre A) was used with an explicit investigation method. I.R., students,[2] and matched controls were required to judge the degree of completion of the chord sequences. For students and matched controls, we predicted that sequences ending on the related tonic chord would be judged as more complete than sequences ending on the less related subdominant chord. For I.R., however, we expected to observe poor discrimination between the two sequence types because of the explicit nature of the task.

EXPERIMENT 3: COMPLETION JUDGEMENTS OF CHORD SEQUENCES

Method

Participants

I.R., her matched controls, and 16 students participated in Experiment 2. For students, number of years of musical practice ranged from 0 to 10, with a mean of 1.6 ($SD = 3.4$) and a median of 0.

Materials

The 24 (12 related, 12 less related) chord sequences played entirely with the acoustic piano sound (Timbre A) from Experiment 2 were used. The experiment was run on PsyScope Software (Cohen et al., 1993).

Procedure

Participants were asked to judge the degree of completion for each sequence by using an 8-point rating scale (from 1 weakly completed to 8 very complete). A very complete sequence was defined as a sequence that provides the feeling of clear closure, whereas an incomplete sequence gives the impression that it is unfinished and should continue. Participants were encouraged to use the entire scale to reflect the different degrees of perceived completion. Judgements were given by pressing one of eight keys. To encourage spontaneous judgements, the response period was limited to 5 seconds with an alerting beep after 3 seconds. The 24 sequences were repeated in two blocks, separated by a short break. For students, sequences were presented in random order. For I.R. and matched controls, one order of presentation was used, and the experimenter wrote down the responses given after the timeout.

Results

To control for differences in the use of the rating scale, completion judgements were individually normalized to z-scores (Figure 5). Z-scores were averaged over the two blocks, and differences between related and less related sequences were analysed by bilateral t tests with either sequences (for I.R., students, and matched controls) or participants (for students) as random factor.

[2] In Experiments 3 and 4, students were tested, since—in contrast to the priming tasks of Experiments 1 and 2 with published student control groups (see Bigand et al., 2001; Tillmann et al., 2006a)—completion judgements have not been tested for these musical sequences and spoken sentences.

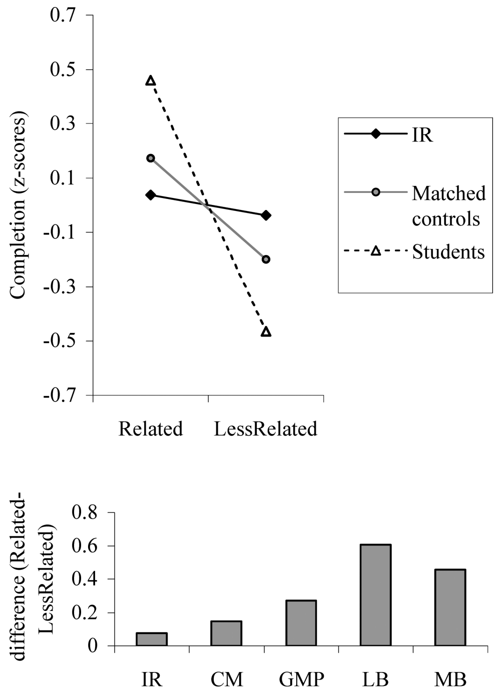


Figure 5. *Top: Completion judgements (normalized to z-scores) for musical sequences in Experiment 3 presented as a function of musical relatedness (related/less related) for I.R., matched controls, and students. Bottom: For I.R. and matched controls, individual differences in response times (normalized to z-scores) between related and less related contexts.*

Students

Related sequences were judged as more complete than less related sequences, $t(15) = 11.86$, $p < .0001$, and $t_2(11) = 7.01$, $p < .0001$. In individual item analyses, the relatedness effect was significant for 14 out of the 16 participants (all ps $< .05$). For one of the remaining participants, an additional analysis showed that the relatedness effect reached significance in the first block ($p < .05$).

I.R.

Completion judgements for related sequences did not significantly differ from completion judgements for less related sequences; $t_2(11) = 0.19$, $p = .85$. An analysis with block as an additional within-subject factor did not reveal a significant influence of block (Fs < 1).

Matched controls

Related sequences were judged more complete than less related sequences, $t_2(11) = 2.15$, $p = .05$. Individual analyses with sequences as the random factor revealed that the difference was marginally significant only for L.B., $t_2(11) = 2.11$, $p = .06$, and M.B., $t_2(11) = 1.89$, $p = .09$.

Differences between implicit and explicit tasks

Response times for Timbre A and completion judgements were compared since these measures were based on the same sequences. The direction of completion judgements was inverted to match higher numbers with longer response times. Individual ANOVAs (excluding L.B. because of low accuracy) were run with task (priming/completion) and relatedness (related/less related) as within-subject factors and sequences as random factor. For I.R., the interaction between task and relatedness was moderately significant, $F(1, 11) = 4.64$; $p = .05$: The relatedness effect was stronger for the priming task than the completion judgements. For C.M., G.M.P., and M.G., the interaction between task and relatedness did not approach significance (ps $> .18$). In an analysis with matched controls (C.M./G.M.P./M.G.) as a between-subjects factor, only the main effect of relatedness reached significance, $F(1, 33) = 16.31$, $p < .001$; the interaction between task and relatedness was not significant ($p = .19$).

Discussion

In contrast to the priming tasks (Experiments 1 and 2), I.R.'s completion judgements did not differ significantly between related and less related sequences. The analyses comparing performance in priming and completion judgements revealed an interaction between relatedness and task for I.R., but not for matched controls. For I.R. only, the observed musical relatedness effect was influenced by the requested task, with a difference between related and less related contexts being present only in the priming paradigm. This outcome suggests that the absence of a musical context effect in I.R.'s completion ratings is due to the explicit nature of the task requirements. However, it might also be argued that I.R. did not understand the concept of completion. The goal of Experiment 4 was to assess whether I.R. is able to understand explicit instructions when these apply to speech. To this aim, short sentences were presented to I.R. and controls, who were asked to judge the degree of completion. The sentences were either grammatically correct or incorrect with incongruent endings.

EXPERIMENT 4: COMPLETION JUDGEMENTS OF SPOKEN SENTENCES

Method

Participants

I.R., her matched controls, and 19 students participated in Experiment 4.

Materials

A total of 34 French sentences with eight syllables were constructed in such a way that the same 17 final words created 17 congruent endings and 17 incongruent endings depending on the previous context. To create some variety, the incongruent endings were constructed in three different ways: (a) French adverbs (e.g., *autant;* so much/as much*)* that provide a complete ending in combination with some verbs (*Françoise n'a jamais bu autant;* Françoise never drank so much), but not with others (*Alice n'a jamais pris autant*, Alice never took so much), were used as final words; (b) in a similar way, adjectives (e.g., *petit;* small) providing a congruent ending in contexts specifying a referential object (*Le pantalon est trop petit;* the trousers are too small), but not without (*La taupe se cache dans le petit;* the mole is hiding in the small) were used as final words. (c) Some French nouns are composed of two words (e.g., *sèche-cheveux*, hair-dryer). The final words of the incongruent version just kept the first word of the composed noun (*Après la douche, il prend le sèche;* after the shower, he took the hair), which in the appropriate context created a congruent ending (*Il trouva sa réponse bien sèche;* he thought that her/his response was very dry). All sentences were recorded with the French voice of the demonstration version of the text-to-speech software BrightSpeech (http://www.babeltech.com/Demos.php). The software applied a simple prosodic contour to reflect an affirmative form of the sentence.

Procedure

Participants were required to judge the degree of completion of the sentences on an 8-point scale (from 1 weakly completed to 8 very complete). Completion was restricted to sentences' content without considering intonation or prosodic features. The 34 sentences were presented in random order to students and in one fixed order to I.R. and matched controls. Other aspects of the procedure were as described in Experiment 3.

Results

As in Experiment 3, completion judgements were individually normalized to *z*-scores (Figure 6), and differences between congruent and incongruent sentences were analysed with bilateral *t* tests with either sentences (for I.R., students, and matched controls) or participants (for students) as a random factor.

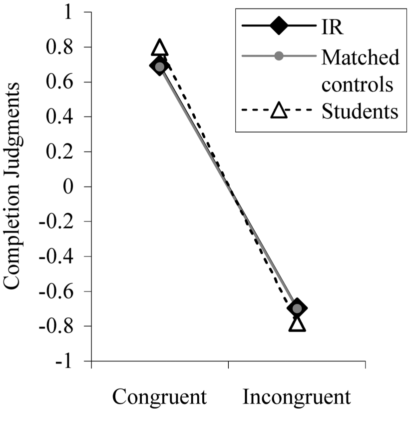


Figure 6. *Completion judgements (normalized to z-scores) for sentences in Experiment 4 presented as a function of ending (congruent/incongruent) for I.R., matched controls, and students.*

Students

Congruent sentences were judged as significantly more complete than incongruent sentences, $t(18) = 32.45$, $p < .0001$, and $t_2(32) = 17.47$, $p < .0001$. Each participant displayed the effect (all ps $< .001$).

I.R.

I.R.'s judgements (averaged over two blocks) indicated that congruent sentences were judged significantly more complete than incongruent sentences; $t_2(32) = 6.96$, $p < .0001$.

Matched controls

Congruent sentences were judged significantly more complete than incongruent sentences, $t_2(32) = 9.82$, $p < .0001$. The difference was significant for each participant (all ps $< .001$).

Discussion

For completion judgements of spoken sentences, I.R. showed the same data pattern as students and matched controls. This outcome suggests that I.R.'s data on musical sequences (Experiment 3) were not due to difficulties in understanding the concept of completion.

GENERAL DISCUSSION

Our study investigated tonal knowledge in the amusic patient I.R. with implicit and explicit investigation methods. Explicit completion judgements of chord sequences confirmed I.R.'s musical disorder (Experiment 3), but the implicit priming paradigm revealed spared musical knowledge (Experiments 1 and 2). For phoneme and timbre identification tasks, I.R. showed harmonic priming as previously reported for students (Bigand et al., 2001; Tillmann et al., 2006a) and replicated here with a matched control group: Target processing was faster in related than in less related chord contexts. This finding replicates in the music domain an observation previously reported in other domains (i.e., language, faces): The perceiver's implicit knowledge is better revealed by implicit than explicit investigation methods.

I.R.'s performance in the harmonic priming experiments is remarkable given the musical sophistication of the manipulated harmonic relations. The related tonic target is the most referential event of the context key, and the less related subdominant target is also a referential event, but to a lesser extent than the tonic. The difference between the two conditions thus corresponds to a subtle difference in abstract musical functions. In addition, experimental stimuli were constructed in such a way that targets never occurred in the previous context so that sensory priming (i.e., priming due to storage of sensory information) did not contribute to the relatedness effect (see Bigand et al., 2003, for a discussion of sensory vs. cognitive influences). I.R.'s priming effect with the present material reveals the existence of subtle anticipatory processes occurring at a cognitive level.

Harmonic priming in healthy listeners has been attributed to automatic musical expectations (Bigand et al., 2001; Justus & Bharucha, 2001; Poulin-Charronnat, Bigand, Madurell, & Peereman, 2005; Tillmann & Bigand, 2004; Tillmann, Janata, Birk, & Bharucha, 2003b). Accordingly, I.R.'s priming effect is best interpreted as spared automatic access to musical knowledge. Explicit completion judgements might require controlled access, which appears impaired in I.R. Thus, implicit knowledge of harmonic structures remains accessible even when explicit judgements are deficient. The observation of I.R.'s failure in explicit judgements is consistent with her prior data. As reported in Table 1, judgements of tonal closure for short melodies were impaired in I.R. (Peretz et al., 1997) in comparison to controls, who were able to distinguish melodies ending on the tonic tone from those ending on other diatonic tones. The explicit search for tonally relevant features does not succeed in accessing the spared implicit tonal knowledge (suggested by the present priming data), but seems to have a rather deleterious impact on these judgements.

Observing differences in performance between explicit and implicit investigation methods does not imply that different knowledge representations or processing components are involved. In other words, the dissociation between impaired explicit knowledge and spared implicit knowledge can be mediated by single-system models of memory in combination with different learning rates (Kinder & Shanks, 2003) or activation levels (Morrison, Bruce, & Burton, 2000). These differences between implicit and explicit knowledge might be differences "in degree rather than in kind" (Cleeremans & Jiménez, 2002; Destrebecqz & Cleermans, 2002). Knowledge representation can thus be conceived of as a graded representation. Implicit knowledge refers to weaker, "poor-quality" representations. These weaker, less stable representations are less available to consciousness, while they are still influencing perception and behaviour. Implicit and explicit investigation methods are thus tapping into the same knowledge representation, but implicit testing methods require lower activation levels than those necessary for explicit, consciously available judgements. Consequently, implicit tests are more sensitive and allow us to reveal processing levels and representations that are not accessible with explicit tests. For example, implicit learning paradigms have shown that amnesic patients and patients with Alzheimer's disease can learn sequences and artificial grammars without declarative knowledge (e.g., Knowlton & Squire, 1994, 1996; Reber, Martinez, & Weintraub, 2003; Reber & Squire, 1998). However, implicit processes are not immune to deficits due to brain lesions or disease. This might depend on the severity of the brain damage or on the tested features (see also Schacter, 1987). More specifically, it has been shown recently that implicit learning is only partly spared in amnesia, depending on the characteristics and the complexity of the to-be-learned systems (Channon et al., 2002; Vandenberghe, Schmidt, Fery, & Cleeremans, 2006). Similarly, syntactic priming in Broca's aphasics might be preserved but it develops more slowly than in healthy individuals (Prather, Zurif, Love, & Brownell, 1997).

The advantage of implicit over explicit methods has also been demonstrated in the musical domain with young children. Six-year-old children differentiate between tonic and subdominant chords in the musical priming paradigm, just as adults do (Schellenberg, Bigand, Poulin-Charronnat, Garnier, & Stevens, 2005), while explicit investigations indicated that it is not until the age of 10 that children are able to differentiate between tonic and dominant chords (Imberty, 1981). Neurophysiological measurements, which do not require explicit judgements from listeners, confirm this early development; 5- and 7-year-olds exhibit distinct evoked potentials for unusual chord sequences (Koelsch et al., 2003). The harmonic priming paradigm is a sensitive method for showing that healthy adults and children without formal musical training have acquired elaborate knowledge about pitch structures. Our study extends this observation to a brain-damaged subject and shows that it is possible to be amusic at an explicit level (i.e., when tested with explicit tasks) without having lost all musical abilities at an implicit level. In other words, an "explicit amusic" may still be somewhat musical at an implicit level. However, the present data do not allow us to conclude that harmonic knowledge in I.R. is "intact" nor that other musical processing components are also spared in I.R. Rather, the present data reveal residual musical knowledge that had not been previously uncovered with explicit investigation methods.

The power of implicit investigation methods raises the possibility that implicit musical knowledge has been unnoticed in other cases of amusia. One amusic condition that is similar to I.R.'s amusic pattern is congenital amusia. Congenital amusia (or tone-deafness) refers to a lifelong musical disorder that cannot be explained by hearing loss, brain lesions, or cognitive and social deficits (e.g., Foxton et al., 2004; Peretz, 2001). If congenital amusics have had the possibility to acquire some tonal knowledge, even if sparse or incomplete, the implicit priming method would be the most adequate tool to reveal it. In a currently ongoing project, we tested nine congenital amusics with the musical priming paradigm using the phoneme discrimination task (unpublished data). The group of congenital amusics obtained a musical priming effect that is comparable to that of normal controls, with facilitated processing for related targets. This musical priming effect suggests that—despite the described pitch perception deficit (Hyde & Peretz, 2004)—congenital amusics have acquired partial musical knowledge about statistical regularities in the musical system. For example, the case Monica (Peretz et al., 2002) cannot detect pitch variations smaller than two semitones in most of the tested situations—except for tone pairs with raising pitch, for which two semitones are detected correctly. This discrimination performance might be sufficient to capture some of the regularities of associations between pitches, leading to some tonal knowledge (including the harmonic relations tested in the priming paradigm), even if sparse and remaining functional only at an implicit level. Future studies will have to specify whether the revealed sensitivity to musical structures extends to melodic lines.

The implicit investigation method of priming has previously revealed harmonic relatedness effects in a patient with bilateral auditory cortex ablations, M.S. (Tramo, Bharucha, & Musiek, 1990). These data suggest that processing of tonal harmony involves regions outside the auditory cortices. After hearing a single chord prime, M.S. provided sensory dissonance judgements on the following target chord that were influenced by harmonic relatedness (despite weak accuracy levels indicating a deficit of consonance/dissonance perception): Accuracy for in-tune targets was better for related than for unrelated target chords, while the reverse was observed for out-of-tune targets. The observed processing advantage of related in-tune targets included sensory priming since some frequencies of upper partials of primes were repeated in the related targets, while the unrelated targets introduced novel frequencies. The cognitive priming effects observed in I.R. in the present study confirm and extend the finding that implicit access to harmonic knowledge can occur despite lesions in the auditory cortex. Yet, in I.R., basic pitch processing might take place in the intact right Heschl's gyrus, as suggested by the comparison between monaural and binaural sound processing (Griffiths et al., 2000).[3] Functional neuroimaging data suggest that musical pitch is further interpreted in the inferior frontal cortex and other temporal and parietal areas (Koelsch, Fritz, Schulze, Alsop, & Schlaug, 2005; Koelsch et al., 2002; Tillmann et al., 2003a, 2006b). The fact that I.R. exhibits a musical relatedness effect despite her right frontal lesion requires further investigation in order to specify the network of brain regions subserving harmony processing, as we discuss now.

Neurophysiological data from healthy adults suggest that the prefrontal cortex is implicated in the manipulation and evaluation of musical structures (Janata et al., 2002; Koelsch, Gunter, Friederici, & Schroger, 2000; Patel et al., 1998a; Zatorre, Evans, & Meyer, 1994) and, more specifically, the inferior frontal cortex with a right-hemispheric asymmetry (Koelsch et al., 2005; Koelsch et al., 2002; Maess, Koelsch, Gunter, & Friederici, 2001; Tillmann, Janata, & Bharucha, 2003a). In a recent functional magnetic resonance imaging (fMRI) study, the neural correlates of harmonic priming were studied in young healthy adults (Tillmann et al., 2006b). As in Experiments 1 and 2, participants performed phoneme and timbre identification judgements on sung sequences and instrumental sequences. The BOLD signal was increased for less related targets over related targets in inferior frontal regions (inferior frontal gyrus in the vicinity of pars opercularis and anterior insula) mainly in the right hemisphere, but also in the left hemisphere with reduced statistical threshold. In addition to inferior frontal regions, which have been under focus, the activation pattern extended to right posterior orbital gyrus, left temporal

[3] Interestingly, in both I.R. and M.S., the processing of consonance was impaired, probably as the result of the lesions in auditory cortices (see Peretz et al., 2001).

regions (anterior superior temporal gyrus, posterior superior temporal sulcus and gyrus, middle temporal gyrus), and right inferior parietal lobe (supramarginal gyrus). Figure 7 displays the activation areas in parallel to I.R.'s computed tomography (CT) scan. I.R.'s lesions encompass the activation area in the right inferior frontal regions, while activation in the left inferior frontal regions as well as in posterior temporal and parietal areas fall in healthy tissue. The comparison between functional neuroimaging data of healthy listeners and I.R.'s lesions together with I.R.'s priming data suggests that implicit processing of musical structures can occur despite damage to right inferior frontal areas. Presently, it is not possible to ascertain whether I.R.'s musical relatedness effect was supported by peri-infarct activation, or by left inferior frontal activation compensating for the right-hemispheric lesion via contralateral disinhibition, or whether—even in the healthy brain—harmonic structure processing involves a neural network emerging from interactions between the observed brain regions. Unfortunately, functional imaging of the patient I.R. is not possible because of the presence of metallic brain clips. Thus, the present observation calls for further functional neuroimaging research in healthy listeners to better understand the neural networks subserving harmonic structure processing.

We might further speculate that inferior frontal regions are involved not only in the implicit processing of tonality but also in explicit, controlled processes that are impaired in I.R. Indeed, in syntax processing of language, the left inferior frontal gyrus is not only activated in implicit tasks (Kang, Constable, Gore, & Avrutin, 1999) but is more strongly activated in explicit tasks (Suzuki & Sakai, 2003). Moreover, right prefrontal activation is reported in explicit, but not in

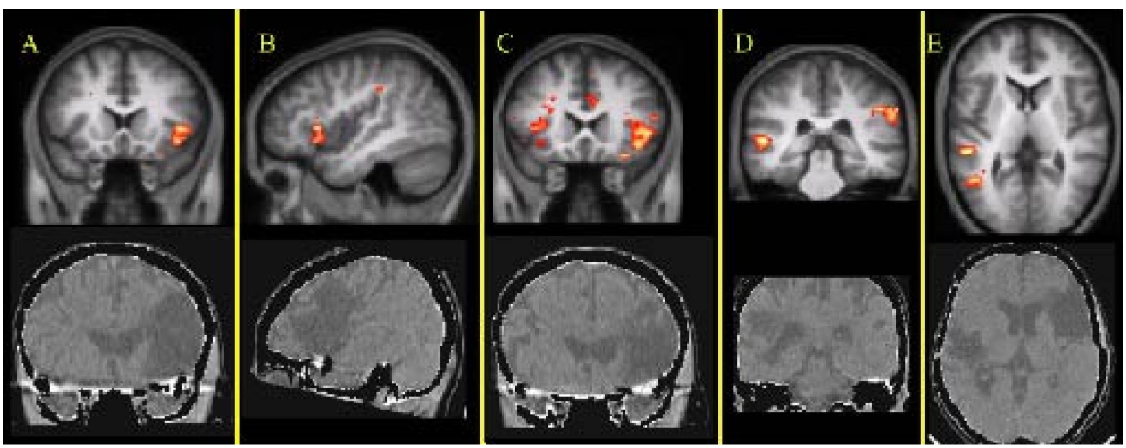


Figure 7. *Functional imaging data of the harmonic priming study presented in parallel to I.R.'s computed tomography (CT) scan. Images are not superimposed because of different reference spaces (Talairach vs. MNI). Functional magnetic resonance imaging (fMRI) activation in anterior superior temporal and posterior orbital gyri are not displayed since activation clusters are situated on the border of the lesion and of a CT scan slice, respectively. Top: Group image showing significant differences in BOLD signal of less related over related targets in (A) and (B) right inferior frontal regions (frontal operculum, anterior insula,* $p < .001$*), (C) left inferior frontal regions (*$p < .005$*), (D) left superior temporal sulcus and right supramarginal gyrus (*$p < .001$*), and (E) posterior superior temporal sulcus and middle temporal gyrus (*$p < .001$*). Displayed slices correspond to the following coordinates in Talairach space: (A)* $y = +15$*; (B)* $x = +43$*; (C)* $y = +18$*; (D)* $y = -33$*; and (E)* $z = +9$*. Activations are superimposed on the averaged T1-weighted anatomical images of all participants. Reported activations were based on sung and instrumental sequences. Region of interest analyses on the fronto-insular area confirmed increased activation for less related targets with each material. (Data from Tillmann et al., 2006b). Bottom: Corresponding slices of I.R.'s CT scan in MNI space with the following coordinates: (A)* $y = +15.3$*; (B)* $x = +43.3$*; (C)* $y = +18.2$*; (D)* $y = -34.4$*; and (E)* $z = +8$ *(the transformation from Talairach to MNI space was realized with the program tal2mni.m by M. Brett, www.mrc-cbu.cam.ac.uk/Imaging/Common/downloads/MNI2tal/).*

implicit learning (Fletcher et al., 2005). Research investigating the neural correlates of consciousness further suggests that specific states of consciousness occur when numerous subsystems interact in a coordinated way. Since explicit processes are linked to conscious access to stored knowledge or memory traces, we suggest that explicit processes might require increased interactive coordination of areas in the neural network. For I.R., this interaction might be impaired due to the lesions in auditory cortices and the right frontal area.

To conclude, the present findings argue for the need to test patients with musical disorders with implicit, indirect methods. Implicit investigations methods are simply more powerful than standard, explicit assessments to reveal residual abilities. This conclusion also has clinical implications for rehabilitation programs of impaired cognitive functions, notably by encouraging learning strategies that rely on spared implicit processing resources (e.g., Bier, Vanier, & Meulemans, 2002; Kessels & de Haan, 2003). In turn, spared implicit musical knowledge may account for I.R.'s report that she still enjoys listening to music (Peretz et al., 1998). The priming paradigm investigates the influence of listeners' musical expectations on target chord processing. Following Meyer (1956), musical expectations play an important role for musical expressivity and emotion. The composer fulfils, violates, or delays listeners' expectancies that develop unconsciously, and from this interplay rise meaningful moments in music. The priming data suggest that I.R. can still develop musical expectancies, which may contribute to her pleasure in listening to music.

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