J Neurosurg 106:1017–1027, 2007

When “Abegg” is read and  (“A, B, E, G, G”) is not: a cortical stimulation study of musical score reading

FRANCK-EMMANUEL ROUX, M.D., PH.D., VINCENT LUBRANO, M.D., JEAN-ALBERT LOTTERIE, M.D., CARLO GIUSSANI, M.D., CLÉMENCE PIERROUX, M.D., AND JEAN-FRANÇOIS DÉMONET, M.D., PH.D.

Institut National de la Santé et de la Recherche Médicale, Unité 825, Fédérations de Neurochirurgie et de Neurologie, Centres Hospitaliers Universitaires, Toulouse, France

Object. To spare the cortical areas involved both in musical score reading and in language, the authors used a score reading task during direct cortical stimulation mapping in musicians undergoing operations for brain lesions. The organization of the cortical areas involved in language and score reading, respectively, was analyzed in relation with these surgical data.

Methods. Seven patients with brain lesions were tested using three language tasks and a score-reading task. Preoperatively, none of them had exhibited significant language or musical ability deficits, and all had a special interest in music. All were involved in professional or amateur musical activities.

Interference in score reading was found in small cortical areas, mainly in the dominant parietal lobe and sometimes in the frontal gyri. During direct stimulation, interference was either language-specific (15 sites), common to language and score-reading tasks (18 sites), or specific to the score-reading task (four sites). Different patterns of score-reading interferences (score-reading arrest, semantic paraphasia) were observed, probably corresponding to different stages of score reading. Postoperatively, some patients showed transitory score-reading difficulties related to the surgical procedure.

Conclusions. The cortical areas involved in score reading can occasionally be distinct from other language areas. This could explain differential word- and score-reading impairments sometimes observed in musicians with brain lesions. Brain mapping for neurosurgical procedures in musicians should ideally be performed using a score-reading task in addition to standard language tasks, especially for mapping in the dominant parietal lobe.

KEY WORDS • music • amusia • cortical stimulation • brain mapping

In 1983, Judd et al.[14] reported the case of a musician who suffered a brain lesion; the musician was one of the major composers and conductors of the twentieth century. In June 1976 when he was conducting an orchestra, he felt as if he had been “hit in the head.”[14,17] He was found to have suffered a left occipital lobe hemorrhagic infarct, and he experienced hemianopia with no aphasia and no writing disturbance. What was stunning in this case was that, although he remained alexic for words, letters, and numbers, he continued to read music very well—he even continued to compose and conduct orchestras. Before him, the famous cases of composers like Maurice Ravel,[2] Vissarion Shebalin,[19] or Jean Langlais,[32] all of whom suffered from dissociated aphasia and amusia, drew physicians’ and researchers’ attention. Investigators hypothesized that music and language processing could be, at least in some parts, anatomically and functionally dissociated in the brain.[6] Several brain activation studies demonstrated the relative independence of functional systems involved in music compared with language.[7,18,25,26] More specifically, all brain activation studies focusing on score reading[20,22,25,28,31,34] underlined that dedicated brain areas (such as the parietal lobes or premotor areas) could be involved in score sight-reading.

For years, we have routinely used direct brain mapping to spare language cortical areas in patients who needed surgical procedures for brain tumors. Different authors showed that score reading deficits could be observed after a surgical brain tumor removal.[17,21,27] Some of the patients treated at our institution were musicians. In an attempt to spare cortical areas involved in score reading, in these patients we used a score-reading task in addition to standard language tasks during brain mapping procedures. Because cases of musicians who need neurosurgical procedures are episodic, the data from these successive brain mappings were prospectively collected by the same team who have used this same protocol for 10 years. To our knowledge, score-reading ability has never been systematically studied in a group of patients by using direct cortical stimulation. The organization of the cortical areas involved in language

Abbreviation used in this paper: fMR = functional magnetic resonance.

and score reading, respectively, was analyzed in relation to these surgical data.

Clinical Material and Methods

Patient Population

Among the patients undergoing surgery for brain tumors or vascular lesions between 1996 and 2005 at our institution, seven were musicians (two male and five female patients) ranging in age from 14 to 66 years (mean age 42 years). They had no language deficit and were prospectively studied using cortical brain mapping performed while the patient completed different language tasks as well as a score-reading task. In five patients the lesion was in the left hemisphere, and it was in the right hemisphere in the other two. These lesions consisted of the following: three low-grade gliomas, two high-grade gliomas, one cavernoma, and one left intraventricular meningioma for which brain mapping was performed before resection via a transcortical approach.

Language Testing

All but one of the patients were French natives. One was born in Germany but had been living in France for more than 25 years and spoke perfect French. Two were bilingual (one German/French, the other French/English). All the patients completed language tests to assess their ability to perform the required language tasks. This testing included evaluation of written and oral understanding, as well as naming, language fluency, reading, computation, dictation, repetition, copy, and object handling. Dysphasic patients (those making > 10% errors in naming tests) were excluded from this study.

The degree of handedness of the patients was assessed using the Edinburgh Handedness Inventory test;[24] handedness is assessed and scores ranging from +100 for completely right-handed patients to −100 for completely left-handed patients are assigned by asking the patient which hand he/she usually prefers to use to do various daily acts. In our study, the handedness indexes ranged between +100 and +70 for six patients, which indicated a clear right-hand predominance. The other patient was left-handed (−50 on the Oldfield test).

Musical Ability Testing

All patients but one were amateur musicians. One was a retired piano teacher. Among the French population, the ability to play an instrument is common (in a population of > 60 million, 8 million people play an instrument as amateurs). The ability to read notes on a score, often learned at school, is rather common among the overall population, although it has often been forgotten.

Preoperatively, musical abilities were evaluated both to rule out a problem in music performance that would have altered overall results (for example, specific disturbance of musical abilities due to tumor) and to compare patients' pre- and postoperative musical abilities. Thus, tests performed for this purpose were aimed at evaluating familiarity with melodies, pitch, and temporal discrimination. First, to test their familiarity with melodies, the patients were asked to distinguish five familiar musical excerpts chosen from among standard old French songs from five supposedly unknown melodies chosen from among the works of minor classical composers (10 tests of 20 seconds each). Then, pitch discrimination was attempted; this was assessed using three unfamiliar musical excerpts (10 seconds each) in which some timing modifications were introduced in the initial melody, thus creating an alternative tune: "contour-violated" (three tests of 10 seconds each), "key-violated" (three tests), and "interval-violated" (three tests) melodies were created based on the model previously described by Liegeois-Chauvel et al.[18] Finally, temporal discrimination was evaluated by creating different meters and rhythms for the initial melodies. Overall, 25 different discrimination tests were performed in each patient. All these data were stored on a special compact disc.

All patients underwent the same tests, during which they were asked to do the following: 1) discriminate between familiar and unknown melodies; 2) identify whether pitch modifications (compared with the initial melody) were present in the excerpt heard; and 3) and indicate where the modifications were. As for rhythm and meter tasks, the patients were asked to tell whether the melody's temporal parameters were different from the initial ones. These tests were chosen because they are easy to perform, quickly done (in 20 minutes), and provide a good basis on which to judge whether the musical functions are mostly preserved in the patients. All patients had normal preoperative musical performance abilities. These patients' clinical and musical data are summarized in Table 1. These tests were performed by the lead author of this study, who has a graduate degree in music.

Choice of Mapping Tasks

Like other surgical teams,[35] in brain tumor operations our usual practice is to perform the "awake surgery" technique,[23] once it is determined if any mapping can be useful in the surgical procedure and if the case is appropriate to such a procedure. The main criterion for testing score reading in our treated patients was the patient's involvement in musical activities and the wish to preserve (by using simple intraoperative tests) the ability to perform musical activities after surgery. The choice of brain mapping tasks at our institution depends on four main, simple factors: 1) the existing literature on the topic; 2) the brain region that has to be explored, because according to the available knowledge of functional specialization of the cortical region, different tasks can be used when testing a particular brain region; 3) the possible competences of the patient in a specialized field (he/she may be bilingual or a musician, for instance); and 4) of course, brain mapping tests need to be simple, tolerable, and able to be performed rapidly (< 45 minutes for the whole procedure).

None of our patients had lesions in the Heschl gyrus, which is known to be critical for sound analysis.[27] We made the determination to use score-reading tasks based on the following criteria: first, the existing literature showed that score-reading ability could be impaired in dominant parietal lobe damage.[11,15,21] Second, cerebral activation studies showed that the right parietal lobe,[28] the left parietal lobe,[20,30,31] and the dominant premotor areas[30] could be in-

TABLE 1

Clinical, language, and musical characteristics of seven musicians with brain lesions in whom presurgical brain mapping was performed to spare score-reading areas

Case No.	Age (yrs), Sex	Handedness	Spoken Languages	Side/Location/ Tumor Type	Instrument/Training/Yrs of Musical Activity
1	14, F	rt	French	lt/superior frontal gyrus/high-grade glioma	flute/music school/3
2	35, M	rt	French/ English	lt/supramarginal/ low-grade glioma	piano/music school/8 during adolescence; had played in a folk band for 10
3	17, F	rt	French	lt/intraventricular/ meningioma*	violin/formal training w/ a private teacher/8
4	65, F	rt	French	lt/supramarginal/ high-grade glioma	piano/retired music teacher/35
5	40, M	rt	French	lt/postcentral gyrus/ low-grade oligodendroglioma	piano/music training w/ a private teacher/6 during adolescence; had played in a folk group for the last 20
6	66, F	rt	French	rt/upper parietal/ cavernoma	piano/music training w/ a private teacher/10 during adolescence; plays piano every wk as a hobby
7	59, F	lt	German/ French	rt/lower parietal/ high-grade glioma	violin/music training w/ a private teacher/10 during adolescence; plays violin every wk as a hobby

* Brain mapping used before transcortical approach.

volved in score reading. Third, playing music was one of the main extraprofessional activities of our patients. Fourth, the score-reading tasks chosen were simple and easy to perform during surgery; score reading appears more readily amenable to direct brain mapping than other musical functions (score-reading mappings were performed after language or motor mappings in < 10 minutes). Before surgery, the whole brain-mapping procedure was explained to the patients, who were told about what they would be asked to do. All the patients and their families gave their informed consent for the study of their functional areas by direct brain mapping.

For this study, our patients were initially asked to do three different tasks: a naming task to detect a standard anomia ("This is a...."), a word-reading task, and an Arabic number–reading task, according to our standard brain-mapping procedure. Then, the patients were asked to read an excerpt of a score (without singing it). For the score-reading task, there were three excerpts of similar difficulty: one from the *"Abegg" Variations*, Op. 1, by Robert Schumann; one from the *Prelude and Fugue for Piano*, No. 9 in E major, Op. 87, by Dimitri Shostakovich; and one from the *Moments Musicaux*, No. 4, D780 (Op. 94), by Franz Schubert. These excerpts were chosen because they are rather easy to read. Stimulation was applied randomly during score reading. Of course, these score-reading tasks were performed by the patient while being monitored by a person who was also able to read scores correctly. Once an error in score reading was detected, the surgeon was informed and the cortical area in question was marked with a small tag representing score-reading interference.

Cortical Mapping Procedures

Patients were all treated using the awake surgery technique. Sleep was first induced in the patients by using mild doses of propofol, and when brain mapping was required they were awakened (then propofol was used again to induce sleep). Three-point head fixation was applied. We used a neuronavigation system in all patients. Anatomical structures were identified according to neuronavigation data and by the shape of the gyri and sulci. The brain was exposed in a standard fashion. Intraoperative cortical stimulation was used to localize functional cortex after determination of the afterdischarge threshold with the aid of electrocorticography. The cortex was directly stimulated using the bipolar electrode of the multifunctional stimulator (1-mm electrodes separated by 5 mm [NIMBUS, Newmedic]). The current amplitude was progressively increased by 1 mA, beginning at 2 mA. We used a standard procedure of stimulation with biphasic square wave pulses of 1 msec at 60 Hz, with a maximum train duration of 4 seconds. We mapped the cortex exposed by the craniotomy, so that in each patient between 12 and 32 different cortical sites were tested. All the patients were tested at the same site for each task. The naming task was performed first, followed by word-, Arabic number–, and score-reading tasks.

When a functional site was found, it was marked by a 0.25-cm^2 sterile tag, and then another cortical area was tested. Our policy was to spare the language or score-reading areas, found by direct brain mapping during the tumor removal, by resecting the tumor tissue no more than 1 cm from eloquent cortex (distance of the resection margin from the nearest functional site).

Conditions of Validation of Language or Score-Reading Sites

To be accepted as a language location site, the functional sites that were found were meticulously tested at least three times. Three consecutive reading errors while stimulation was being applied were considered significant. When a positive site was found, it was not immediately tested again. Other sites were stimulated before repeated stimulation was applied on this positive site. At the end of the language mapping, language- or score-specific sites that were found were confirmed by alternate mapping in both tasks so that these would be carefully validated. Although this can be a matter of debate, once the electrocorticographic stimulation threshold was found, all cortical areas were tested using this threshold. Sites showing no reproducible anomia, speech arrest, or score-reading arrest were not included in this study. Cortical mapping procedures were videotaped in all but one patient in this series. The patient's answers were also recorded using a microphone placed near his or her mouth (both as evidence of the patient's cortical organization and to be further analyzed in team meetings). A picture of the brain after each mapping procedure was systematically completed, along with written descriptions of each mapping procedure finding. Intraoperative photographs of the brain were taken after the interference sites in the naming task (sites tagged [L]), the word-reading task, or the Arabic number–reading task (sites tagged [R]) were marked. Small tickets representing score-reading interference [♬R] sites were used in the intraoperative photographs. Sites with no interference found for the tested tasks were also identified (negative sites were tagged [N]). To improve the understanding of the intraoperative photographs, cortical sites producing no language or score-reading impairment were not systematically noted with a sterile tag.

Postoperative Tests

Postoperatively, the patients were asked to perform the same tests as preoperatively to detect any language or musical difficulty. The results were compared with those of the intraoperative tests.

Results

Overall Cortical Mapping Findings

All seven patients performed four tasks (standard naming, word reading, Arabic-number reading, and score reading) without any problem. The two bilingual patients were asked to do naming, word-reading, and Arabic number–reading tasks in their second language as well. Thus, a total of 34 brain mapping studies were made in our seven patients.

Speech arrests, anomia phenomena, or hesitations during the object naming or reading tasks were found 132 times (in common or distinct sites; 36 sites in all). No vocalization phenomenon was found. For all the patients of this study, the largest current that did not evoke afterdischarges ranged between 3 and 5.8 mA. None of the patients had generalized seizure intraoperatively. Partial seizures were observed twice but were rapidly stopped by cold Ringer lactate and serum irrigation. Like other language interference sites, score-reading interference sites found within the cortex could be extremely localized. Some were found specific to the function tested, but others could be common to two, three, or four tasks. For each cortical region tested, the following paragraphs present specific findings (location, specificity, and possible mechanisms of interference).

Word- and Arabic Number–Reading Interference Sites

Word-reading or Arabic number–reading interference sites were found in five patients, in the posterior temporal, the supramarginal, and in the frontal gyri. These sites were occasionally reading-specific (as in the patients in Cases 2, 4, and 5) but were also common with naming interference sites. Reading interferences consisted of standard reading arrest, confusion, unintelligible reading, or paraphasias. Word-reading or Arabic number–reading interference sites could be common but also specific to only one of those different scripts. In this series of patients, the sites specific to either word- or Arabic number–reading tasks were only found in the supramarginal gyrus. No reading interference site was found in the right parietal lobe of the patients in Cases 6 and 7.

Object-Naming Interference Sites

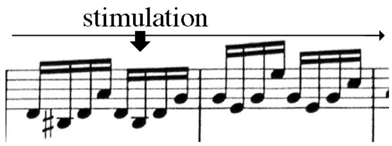
Object-naming interference sites were found in patients in Cases 1 through 5 in their left temporal, supramarginal, and frontal gyri. In the patient in Case 2 (who was bilingual in French/English), specific first-language naming interference sites were found in the posterior part of the superior temporal gyrus. In the patients in Cases 6 and 7, no naming site was found in the right parietal lobe.

Score-Reading Interference Sites

Global Localization of Score-Reading Sites. In the left hemisphere, at least one score-reading interference site was found in all of the five patients. Twenty-one score-reading interference sites were detected. Score-reading interference sites were found in the superior, middle, and inferior frontal gyri (four sites); in the supramarginal gyri (seven sites); in the posterior part of the superior temporal gyrus (three sites) and of the middle temporal gyrus (one site); and in the upper parietal lobe around the intraparietal sulcus (two sites). Four "motor" score-reading sites were found in the precentral gyrus. They were extremely well localized (1 cm^2) within the limit of the surgical exposure, and errors were evoked only twice in any uninterrupted area of cortex larger than 2 cm^2. The margins of these sites were usually distinct, and the displacement of the electrode within an adjacent cortical area located in the same gyrus did not produce any score-reading interference. These sites were common to other functional sites but were sometimes score reading–specific. In the patient in Case 1, we found a score-reading site close to the tumor (< 2 cm). In other patients, all the score-reading sites found were farther than 2 cm from the tumor. Whenever possible, the cortical resections or the approaches were performed to avoid functional sites and especially score-reading sites. No score-reading interference was found in the right parietal lobe of the patients in Cases 6 (right-handed) and 7 (left-handed).

Interference Types and Their Localizations. Score-reading interferences were varied. The typology of score-reading interference evoked by direct cortical stimulation can be summarized as follows:

1) Repeated errors, hesitations, or difficulty verbalizing the score reading (five sites).

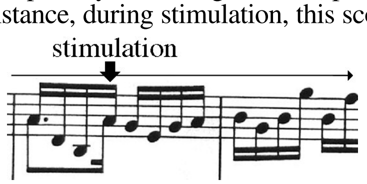


For instance, this score was read as follows: "D, B, D, A, D, B, D ... G ... is that right?... G again.... D? no ... C? no ... E ... that's E...." These types of interference were found in different left hemispheric regions, close to the intraparietal fissure (Cases 3 and 5), in the posterior part of the superior temporal gyrus (Case 2), or in the superior frontal gyrus (Case 1).

2) Fluent at the score-reading task but obvious "verbal" paraphasias (confusions of notes; four sites).

For instance, this score was read: "G, C, G, C, F, D, F, D, G, F, D, D, F, A, E, A, C, F, B, B...." Similar to paraphasia phenomena for words, score reading was fluent but incorrect once stimulation was applied on the cortex. These interferences were found in the anterior and lower part of the left supramarginal gyri in the patients in Cases 2 and 4. No score-reading paraphasia was observed anywhere else. Neither phonemic paraphasia nor jargon aphasia was observed.

3) Total incapability of reading a score (speech arrest; 12 sites). For instance, during stimulation, this score

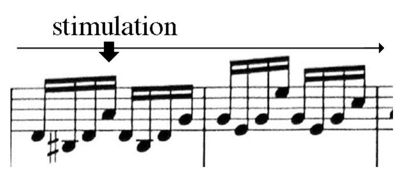


was read: "A, D, B, A, G...." The patient abruptly stopped reading as soon as stimulation was applied (Fig. 1). These interferences were found in different left hemispheric regions, close to the intraparietal fissure (Cases 3 and 4), in the posterior part of the superior temporal gyrus (Case 2) and the middle temporal gyrus (Case 3), in the middle frontal gyrus (Case 1), and in the Broca area (Case 3). These abrupt score-reading arrests were also noted in the precentral gyrus (motor areas). They were due to blockage of the final, articulatory pathways of the score-reading task, and were not specific to score reading. Interference types and their localizations are summarized in Fig. 2.

Specificity of Findings

All authors presenting direct brain mapping data face the challenge of the spatial and the anatomical localization of functional responses. Direct brain mapping using four different tasks can yield a large amount of data. To address that issue, we decided to separate score-reading sites from all the other language sites (naming, word-reading, and Arabic number–reading sites). For each patient, specific findings are presented in Fig. 3. Some score-reading sites were found that were specific to other functions tested in this study (word- or Arabic number–reading and object naming). In this figure, we separated specific score-reading sites from all other specific language sites (naming and/or word-reading and/or Arabic number–reading interference) or from sites in which score-reading interference was common with language interference. To understand this paper, it is essential to know that when, for instance, we say that a site is "score-reading specific," it means that, among the functions we tested, no other function was found to be disrupted after applying direct electrical stimulation at this site (that is to say, this site could be involved, however, in other functions not tested in this study).

Findings on score reading–specific sites are twofold: 1) score reading–specific sites were found infrequently (they were found in the patients in Cases 1, 4, and 5 in two different locations); and 2) in this series of patients, these score reading–specific sites were found in the left superior frontal gyrus (Case 1) and in the posterior part of the left supramarginal gyrus, close to the intraparietal fissure in Cases 4 and 5 (Fig. 4). Although it is rare, observing such a phenomenon during brain mapping can be stunning. For instance, during the stimulation of a cortical area localized in the junction between the middle and superior frontal gyri, the patient in Case 1 was unable to read the following score:



She read "D, B, D, A, F, right?... A ... no ... I don't know ... C?", but during stimulation of the same cortical site, she could read normally the sentences presented to her (example: "La voiture est bleue ou rouge - le soleil se leve aussi...." ["The car is blue or red - the sun also rises."]). Series of numbers ("34 - 5 - 49 - 50 - 81 ...") were also read without any problem during stimulation of this cortical area. The naming task was performed normally as well during stimulation of this area.

Score-Reading Site Organization in Left Hemisphere and Proficiency in Score Reading

For the patients in Cases 2, 4, and 5, these individuals had been practicing score reading for more than 15 years; they were more proficient at it than the patients in Cases 1 and 3. Neither did we find more score-reading sites in these patients (a total of 10 sites) than in others (a total of 11 sites), nor did we find more specific score-reading sites. Consequently, in this small group of patients we cannot conclude that score-reading proficiency influences the organization of score-reading cortical sites.

Postoperative Evaluation

Language. All patients underwent complete postoperative language evaluation. Although immediate postoperative language difficulties came up in the patients in Cases

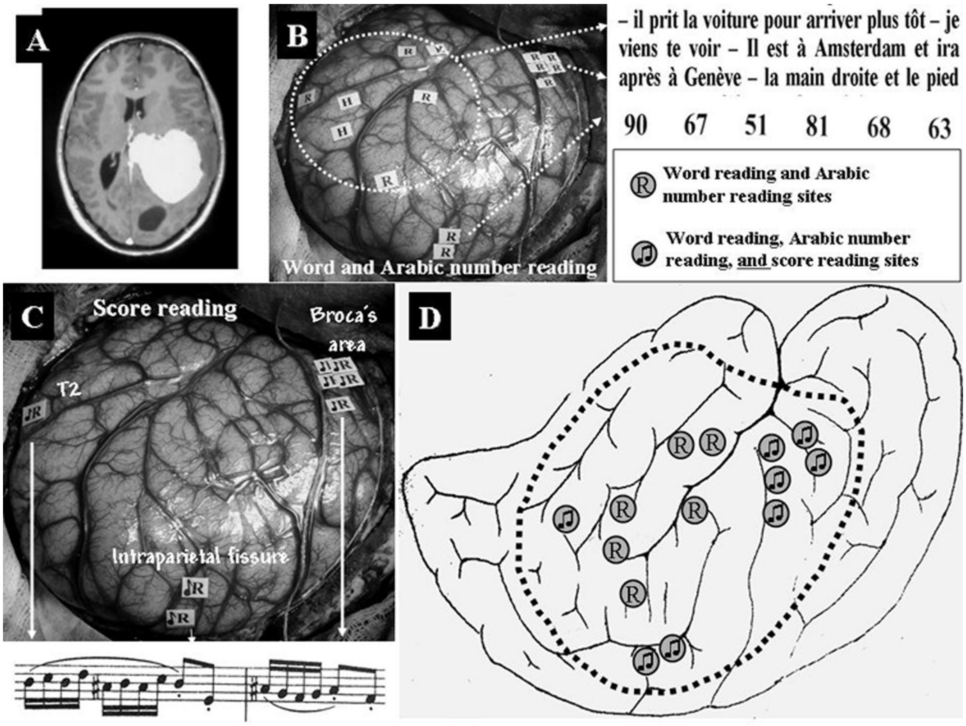


FIG. 1. Case 3. Illustrations of the localization of score-reading areas compared with other reading tasks. A: Axial magnetic resonance image demonstrating a left intraventricular meningioma in this 17-year-old violinist. Brain mapping was performed before a transcortical approach was used to resect the tumor. B: Intraoperative photograph showing the results of the word- and Arabic number–reading tasks. Interference in the reading tasks was found in the perisylvian areas, in the upper part of the supramarginal gyrus, in the precentral gyrus, and in the Broca area. C: Intraoperative photograph showing results of the score-reading task. Two areas of score-reading interference were found close to the intraparietal fissure in areas common with the reading tasks. In the frontal areas (precentral gyrus and ramus opercularis) and in the middle temporal gyrus, score-reading interferences were also common with other reading interference. Nevertheless, in the temporal areas, some sites eliciting word- and Arabic number–reading interference demonstrated no score-reading interference. D: Schematic representation of the interference found in word-, Arabic number–, and score-reading tasks. In this case, although no area specifically involved in score reading was found, the perisylvian areas found to be involved in word- and Arabic number–reading were not involved in score reading.

1, 2, 3, and 4, none of them showed a significant decrease of his/her preoperative global language performance when evaluated within 3 to 8 weeks postoperatively. The patient in Case 3 resumed school with no difficulty 1 month after her operation and passed her examination at the end of the year. Nevertheless, subtle writing or reading difficulties were noted during language testing. The patient in Case 2, who underwent surgery for a low-grade astrocytoma in the left supramarginal gyrus, had difficulties in spelling words. He resumed his work (as an engineer in the gas industry) 2 months after his operation. In the patients in Cases 1 and 4, we found deteriorated handwriting (their letters were badly shaped) in postoperative writing samples compared with those written preoperatively. This did not improve when these patients were treated using radiotherapy for their high-grade gliomas. No postoperative language difficulty was noted in the patients in Cases 5, 6, and 7.

Music. Postoperative evaluations were completed by the first author of this study within 1 and 3 months postsurgery. None of the seven patients had a significant decrease postoperatively in their "familiarity with the melodies," "pitch discrimination" and "temporal discrimination," and "rhythm" and "meter" tests compared with preoperative findings. During this postoperative testing, we evaluated the patients' performances in score reading and in playing their instruments just as we did before surgery. No difficulty in score reading was detected during evaluations conducted several weeks after surgery. Nevertheless, we had previously noted that a few days after the operation, the patients in Cases 1 and 4 showed difficulties in score reading. In the patient in Case 1 we found a score-reading interference in the area close to the tumor (between 1 and 2 cm), and the difficulties in score reading could be explained by this proximity. Although this area was preserved, it was close to the limits of surgical removal. Three days after surgery, when we asked her to read the *Abegg Variations* score by Robert Schumann, we observed that she was able to read the title, the name of the composer, and the dedication almost perfectly, but reading the score was very difficult for her and she made errors. This differential reading impairment was also observed when she was tested with other materials (different sentences and scores) and was recorded on videotape. The patient in Case 3 (in whom we operated via a middle temporal gyrus transcortical approach) had postoperative global reading difficulties that resolved a few weeks later. Reading difficulties were not specific to scores. Overall, score reading became normal 2 months postsurgery for the patients in Cases 1 and 4.

Finally, to evaluate their instrumental abilities, the patients were asked to come to the clinic with their scores and their instruments when possible (for instance, an electronic keyboard was installed in the clinic for the pianists), or they were evaluated at home. Although these results are subjective, the patients in Cases 1, 4, and 5 noted some difficulties in playing their instruments as well as they had before surgery. For instance, the patient in Case 5, who used to play Chopin's "Valses" or French folk music, had more trouble in playing them as easily as before. The patient in Case 4, a retired music professor, played some Preludes and Fugues of the *Well-Tempered Clavier* by J. S. Bach. Her musical performance was good, but she said she had played better before her disease and her surgery. Nevertheless, because several factors—such as the patients' postsurgical stress or fatigue—could interfere with musical evaluations, the real meaning of the difficulties expressed by these patients is questionable.

Discussion

In this brain mapping study, interference in score reading had the following parameters: 1) it was found in small cortical areas; 2) it was sometimes anatomically distinct (totally or partially) from other language functions; 3) it was predominantly located in the dominant supramarginal gyrus or close to the intraparietal fissure; and 4) it was variable in its patterns (probably corresponding to different stages of musical notation analysis processing). In the following sections, we will discuss the clinical studies, mainly based on selective acquired language deficits in musicians, and the research studies in which brain-mapping tools were used to investigate how the human brain analyzes musical notation. We will discuss our data in relation to these studies.

Deciphering Musicians' Brain Lesions

The form of musical notation used in the Western world today has traditionally been believed to have been initiated by Guido d'Arezzo in his book *Micrologus* (written circa 1030), and notation has improved in the course of the succeeding centuries. Although western musical notation is graphically and functionally different from any of the writing systems (alphabetic, syllabic, or logographic) used nowadays, this was not always the case during the course of human evolution. Drawings (in the Babylonian language), alphabetic letters (in ancient Greek), ideographic characters (in ancient China), or Arabic numbers (as the current system of notation of traditional music in China) have been used to notate music.[1] Score reading is one of the first stages leading to taking up an instrument to play music. Moreover, deep conceptual and phylogenetic links exist between hand movements, music, and mathematics. Like some mathematical functions, writing, or hand-shape representations,[8,10] sight-reading of scores based on spatial representations could involve the dominant parietal lobe and its cross-modal associations.[30] This close link between musical notation and coordinated finger movements was used by some musicians to create some musical notations that were hand-based (such as the "Guidonian hand," a system of assigning a certain note to each part of the hand).

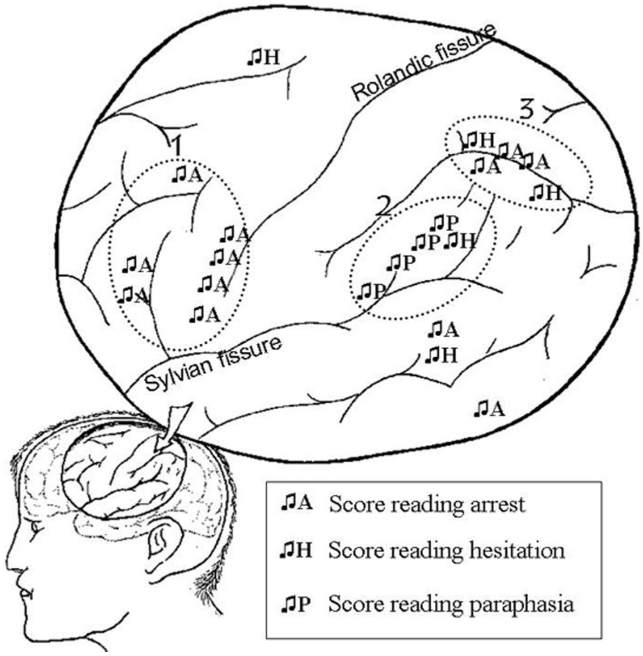


FIG. 2. Schematic representation of the types and localization of score-reading interference in our five patients in whom the left hemisphere was studied. Three main groups can be classified. In Group 1, abrupt score-reading arrests were mainly found in the inferior frontal (Broca area) and the precentral gyri. In Group 2, all score-reading paraphasias were found in the supramarginal gyrus, and in Group 3, different types of score-reading interferences (abrupt reading arrest or reading hesitation) were detected in the upper part of the supramarginal gyrus, close to the intraparietal fissure.

Because music can be divided into several components, there exist uncertainties about the exact structures involved in musical cognition.[16] Although there are numerous cases in the neurological literature about differential deficits between language and music, reports of more specific differential impairments between words and score reading have been more rare.[3,5,13,14,29,32,33] What articles have appeared have mainly been reported cases of spared score reading in aphasic patients. Souques and Baruk[33] reported on a piano professor who was unable to read a single word after a stroke involving the posterior part of the superior, middle, and inferior temporal gyrus, but who was still able to read scores and copy music. Assal[3] described the case of a professional pianist with a typical Wernicke aphasia, including alexia and agraphia for words, who had no amusia and could read scores correctly: "It is stunning to see that melodies and scores are rapidly identified while their written titles (were) not." Also impressive is the case of the blind French organist and composer Jean Langlais (1907–1991), who lost the ability to read the Braille alphabet but was still able to read Braille musical scores after a left hemispheric stroke.[32] Selective preservation of musical writing in a context of agraphia for words and letters has also been described in a piano teacher who suffered a stroke involving the left supramarginal and angular gyri.[4]

The reported cases of the reverse situation (spared word reading with impaired score reading) are not clear-cut. Many reported cases date from a long time before the in-

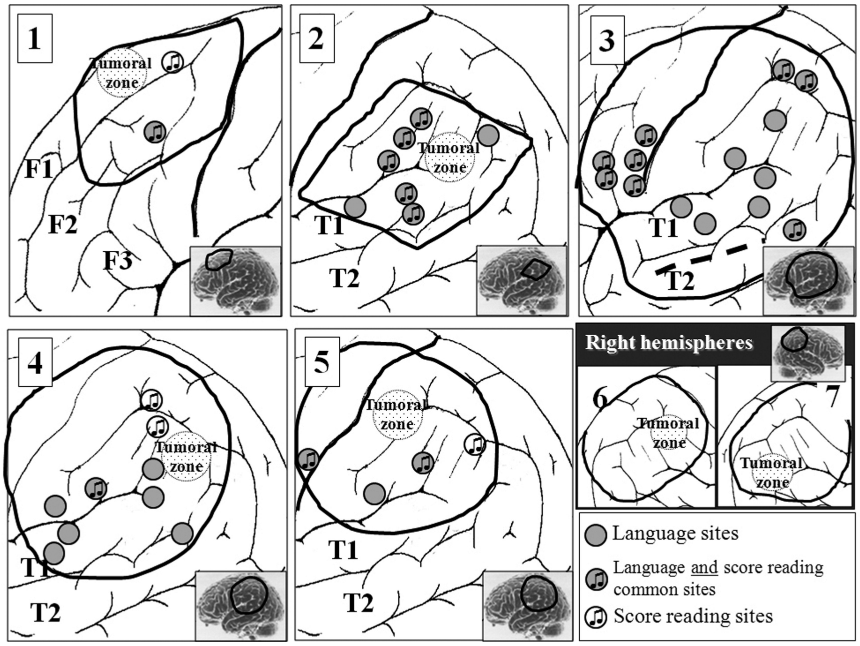


FIG. 3. Cases 1–7. Schematics of the localization of the language interference sites ("language interference" includes naming, and/or word-reading, and/or Arabic number–reading interference) and the score-reading interference sites found in each patient. Specific score-reading sites (*white circles* containing eighth notes) are separated from other language sites (no score-reading interference: *gray circles*) and from sites that were common to language and score-reading interference (*gray circles* containing eighth notes). Counting both hemispheres, four score reading–specific sites were found in Cases 1, 4, and 5. The *solid line* denotes the area of the craniotomy, and the *dashed line* outlines the cortectomy in the patient in Case 3 (mapping was performed before the resection of an intraventricular meningioma via a transcortical approach).

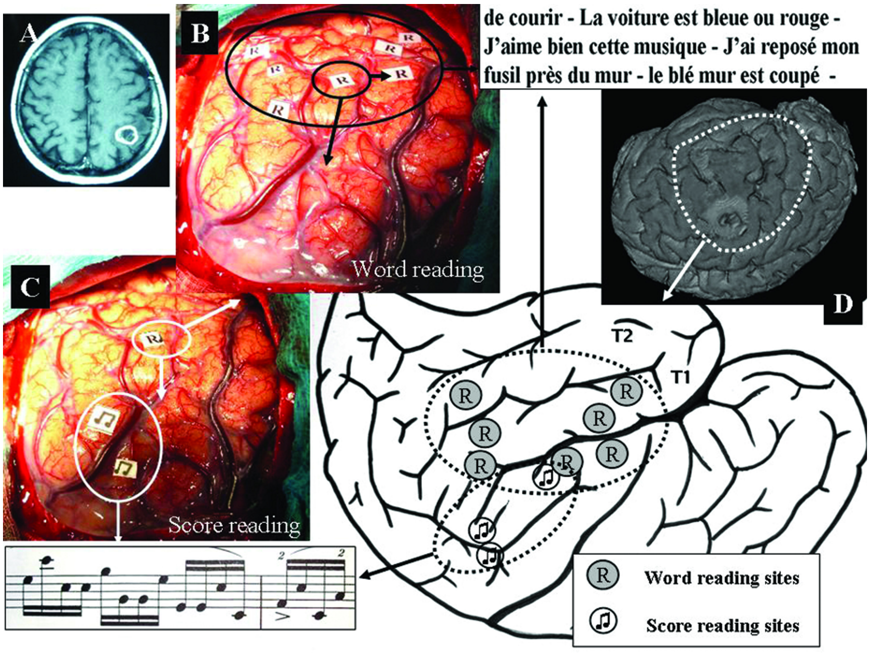


FIG. 4. Case 4. Illustrations of the specificity and localization of areas involved in score reading in the left hemisphere. In this case, specific score-reading interference was found in the dominant parietal lobe. A: Axial magnetic resonance image obtained in a retired piano teacher who was suffering from a high-grade glioma located in the left inferior parietal lobe. B: Intraoperative photograph showing results of the word-reading task used for brain mapping. Interference [R labels] was found in the perisylvian areas. C: Intraoperative photograph showing results of the score-reading task used for brain mapping. Interference was found close to the intraparietal fissure, in the upper part of the supramarginal gyrus. One site in the supramarginal gyrus (paraphasia) was common to word- and score-reading tasks *(white arrows)*. D: Schematic representation of the interferences found in word and score reading.

troduction of modern tools for cerebral imaging.[14] "An attempt to find an acceptable reported case of loss of ability to read musical notation without dyslexia or other evidence of disordered higher brain function has proven unsuccessful" wrote Henson in 1977.[12] Recently, however, Cappelletti et al.[9] reported the case of a professional musician who had a specific impairment in music reading and writing after sustaining left posterior temporal lobe and small right occipitotemporal strokes. She retained the ability to read aloud letters, words, numbers, and symbols, including musical ones. Pure musical agraphia (without aphasia, musical alexia, or sentence agraphia) has also been described after left upper parietal lobe damage sustained during meningioma removal.[21] All of these clinical reports on musicians with brain lesions who experienced differential impairments between standard word reading and score reading suggested that the neural substrate involved in score reading or writing could be, at least at some stages, anatomically separate from word/letter processing. In 1919, on the basis of the only clinical observations of the first cases of word/score reading defects, Henschen[11] hypothesized that score- and word-reading "centers" could not be necessarily associated and that the score-reading function could possibly be located "in the vicinity of the angular gyrus or the intraparietal fissure."

What Part of the Brain Reads Music?

Almost a century after Henschen's statement, all brain activation studies focusing on score sight-reading[20,22,25,28,31,34] have pointed out the important role of dominant parietal regions in score reading, and have confirmed the relative independence of word reading compared with score reading. The first study is that of Sergent et al.,[31] published in 1992. Using positron emission tomography scanning, they demonstrated that brain activation during score reading was located in the left occipitotemporal junction, in the posterior part of the left supramarginal gyrus, and in the inferior parietal lobules of both hemispheres. They concluded that score-reading networks paralleled the neural substrates of verbal processing but were distinct from it because the spatial nature of musical notation required the superior parietal lobe. More recently, these findings have been globally confirmed by other authors by using fMR imaging.[20,28,34] Meister et al.[20] showed activations of a bilateral frontoparietal network comprising the premotor areas, the precuneus, and the medial part of Brodmann area 40 during sight-reading. Using fMR imaging contrasts between the musical notation and the verbal or numerical notation tasks, Schon et al.[28] found specific major foci of activation in the right occipitotemporal junction, superior parietal lobule, and the intraparietal sulcus for score reading. Other researchers found a specific activation in the right transverse occipital gyrus in eight musicians reading scores compared with text reading.[22] This right fusiform gyrus involvement in score reading, paralleling the visual word analysis in the left one, has also been found by others.[25,28] Finally, studying not only the ability to sight-read scores but its training over several weeks, Stewart et al.[34] found activation of bilateral superior parietal cortex and of the left supramarginal gyrus. The results of these studies are summarized in Fig. 5. As illustrated in this figure, using noninvasive brain mapping tools, most authors showed that the dominant and nondominant inferior lobes are important in score reading. Using direct brain mapping, we confirmed the role of the left inferior parietal lobe in score reading.

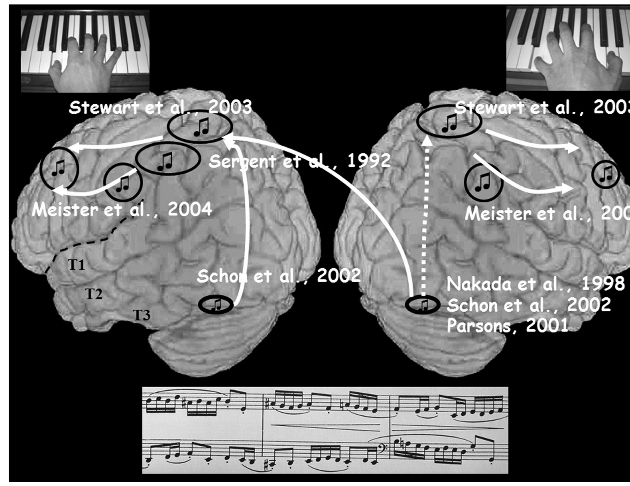


FIG. 5. Schematic illustrations showing a summary of the findings of the main brain activation studies on score reading. Left and right hemispheric regions involved in score reading are underlined *(ovals)* with possible pathways designated *(white arrows)*. Several authors (Nakada et al., 1998; Parsons, 2001; and Schon et al., 2002) underlined the major role of the right inferior temporooccipital lobe. Using fMR imaging or positron emission tomography scanning, Sergent et al., Stewart et al., and Meister et al. showed that the left parietal lobe (mainly the supramarginal gyrus and the intraparietal fissure) was activated during score reading in musicians. Other regions, such as the left inferior temporal lobe (Schon et al., 2002), the right parietal lobe (Stewart et al., 2003) and both frontal lobes (Meister et al., 2004) could also be activated during score-reading tasks in healthy volunteers.

As claimed by Sergent,[30] there is probably no "musical reading center," but a network of structures participating in score reading. Although not found in all studies,[31,34] activation of the right fusiform gyrus could correspond to the first stage of note analysis. Musical notation could subsequently be processed in the left occipitoparietal areas. Children learn to read scores by analyzing the position of the notes on a staff. This spatial analysis of the name of the notes by reference to a key is followed by positioning fingers on the instruments. Note or score reading require a spatial analysis. This reading process is clearly different from word reading. The activations of the parietal lobes in score reading could be consistent with the involvement of the visuospatial (that is, dorsal) visual stream.

The results of our study confirm the role of the dominant inferior parietal lobe and the intraparietal sulcus in note reading. As in many other brain functions,[23] score reading is sustained by small cortical areas. In our patients, these areas were found in common with other language functions tested, or specific to score reading. A certain degree of variability in cortical organization was often noted in individuals during brain mapping. The reasons for this discrepancy are probably multifactorial. Several factors could influence score-reading organization: the age at which score reading started, the effects of training, and proficiency. Whatever the factor involved, we hypothesize that the existence of dedicated areas for score reading could explain cases of differential or selective word- versus note-reading impairments seen in musicians' brains that have been altered by a lesion.

Limits of the Study

Sight-reading (deciphering a score and playing it on an instrument) or even simple score reading is a complex process. Intraoperative mapping of score reading has obvious limitations. We artificially separated score reading from other musical aspects like motor execution on an instrument or note singing. The score-reading task we chose for this study proved useful because it gave online access to the performance of the treated patient. The localization of small areas of the cortex involved in score reading becomes possible, but the whole process of musical understanding cannot really be assessed—and must be far more complex. Moreover, questions remain regarding whether the score-reading areas we detected are indeed necessary for musical reading and need to be preserved. Although we observed postoperative score-reading difficulties, they were further overcome by compensatory mechanisms. We think that this study, because of the limited number of patients, does not allow us to reach unequivocal conclusions about this issue. Finally, our brain mapping did not allow complete exploration of all the neural structures possibly involved in a complex task like score reading. Many cortical areas remain inaccessible to direct stimulation, either in relation to their sulcal localization, or because they are localized either beyond the surgical exposure or in regions that are rarely explored, such as the inferior temporoparietal areas. These limitations must be taken into account when analyzing the results of direct electrical stimulation studies.

Conclusions

Using the symbolism of musical letters to create a link between letters and notes, in 1830 Robert Schumann wrote his *Abegg Variations*, Op. 1, with a musical theme using the notes "A, B, E, G, G" in honor of a young pianist, Meta Abegg. Whatever the numerous links existing between letters, numbers, and notes, we know that language and music can be considered as different cognitive entities, and that they do not always share the same functional and anatomical systems. Studies of patients[9,14] and recent researches[20,28,31] have pointed out the possible independence of the processing of word and score reading in the brain. When using direct cortical stimulation, we also observed that cortical areas involved in score reading could occasionally be distinct from other language functions, and that the reverse was also true. As in brain lesion or brain activation studies, direct cortical stimulation confirms the role of the dominant supramarginal gyrus and the region of the intraparietal fissure in score reading. In practice, these results, when interpreted with the evidence from the literature, lead us to suggest that clinicians should use a score-reading task in musicians who undergo direct brain mapping for brain tumor or epilepsy surgery, especially in the dominant parietal lobe.

Acknowledgments

We thank Denise Géblé for supplying us with the bibliography for this work, and Noëlle Ricard, Sylvie Simonnet, and Christiane Lubrano for editorial assistance. We are also in debt to Jacqueline Simorre for her useful comments on the manuscript. We thank Dr. Sergio Boetto for entrusting his patients to us, and Christel Poux and Corinne Vidal for assistance during the score-reading mapping.

References

1. Abromont C, De Montalembert E: **Guide de la Théorie de la Musique.** Paris: Fayard et Lemoine, 2001
2. Alajouanine T: Aphasia and artistic realization. **Brain 71:** 229–241, 1948
3. Assal G: [Wernicke's aphasia without amusia in a pianist.] **Rev Neurol (Paris) 129:**251–255, 1973 (Fr)
4. Assal G, Buttet J: [Agraphia and preservation of music writing in a bilingual piano teacher.] **Rev Neurol (Paris) 139:**569–574, 1983 (Fr)
5. Assal G, Hadj-Dijilani M: [A case of bilateral lesions in the temporal convexity: attempt to define symptoms.] **Cortex 12:** 169–174, 1976 (Fr)
6. Basso A, Capitani E: Spared musical abilities in a conductor with global aphasia and ideomotor apraxia. **J Neurol Neurosurg Psychiatry 48:**407–412, 1985
7. Besson M, Schon D: Comparison between language and music. **Ann N Y Acad Sci 930:**232–258, 2001
8. Butterworth B: **The Mathematical Brain.** London: Macmillan, 1999
9. Cappelletti M, Waley-Cohen H, Butterworth B, Kopelman M: A selective loss of the ability to read and write music. **Neurocase 6:** 332–341, 2000
10. Geschwind N: Disconnexion syndromes in animals and man. I. **Brain 88:**237–294, 1965
11. Henschen S: Clinical and anatomical contributions in brain pathology. **Arch Neurol Psychiatry 13:**226–249, 1925
12. Henson RA: Neurological aspect of musical experience, in Critchley M, Henson RA (eds): **Music and the Brain: Studies in the Neurology of Music.** London: Heinemann, 1977, pp 3–21
13. Hinshelwood J: Four cases of word-blindness. **Lancet 1:**358–363, 1902
14. Judd T, Gardner H, Geschwind N: Alexia without agraphia in a composer. **Brain 106:**435–457, 1983
15. Kawamura M, Midorikawa A, Kezuka M: Cerebral localization of the center for reading and writing music. **Neuroreport 11:** 3299–3303, 2000
16. Lechevalier B, Platel H, Eustache F: [Neuropsychology of musical identification.] **Rev Neurol (Paris) 151:**505–510, 1995 (Fr)
17. Levin HS, Rose JE: Alexia without agraphia in a musician after transcallosal removal of a left intraventricular meningioma. **Neurosurgery 4:**168–174, 1979
18. Liegeois-Chauvel C, Peretz I, Babai M, Laguitton V, Chauvel P: Contribution of different cortical areas in the temporal lobes to music processing. **Brain 121:**1853–1867, 1998
19. Luria AR, Tsvetkova LS, Futer DS: Aphasia in a composer (V. G. Shebalin). **J Neurol Sci 2:**288–292, 1965
20. Meister IG, Krings T, Foltys H, Boroojerdi B, Muller M, Topper R, et al: Playing piano in the mind—an fMRI study on music imagery and performance in pianists. **Brain Res Cogn Brain Res 19:**219–228, 2004
21. Midorikawa A, Kawamura M: A case of musical agraphia. **Neuroreport 11:**3053–3057, 2000
22. Nakada T, Fujii Y, Suzuki K, Kwee IL: 'Musical brain' revealed by high-field (3 Tesla) functional MRI. **Neuroreport 9:** 3853–3856, 1998
23. Ojemann G, Ojemann J, Lettich E, Berger M: Cortical language localization in left, dominant hemisphere. An electrical stimulation mapping investigation in 117 patients. **J Neurosurg 71:** 316–326, 1989
24. Oldfield RC: The assessment and analysis of handedness: the Edinburgh inventory. **Neuropsychologia 9:**97–113, 1971

25. Parsons LM: Exploring the functional neuroanatomy of music performance, perception, and comprehension. **Ann N Y Acad Sci 930:**211–231, 2001
26. Platel H, Price C, Baron JC, Wise R, Lambert J, Frackowiak RS, et al: The structural components of music perception. A functional anatomical study. **Brain 120:**229–243, 1997
27. Russell SM, Golfinos JG: Amusia following resection of a Heschl gyrus glioma. Case report. **J Neurosurg 98:**1109–1112, 2003
28. Schon D, Anton JL, Roth M, Besson M: An fMRI study of music sight-reading. **Neuroreport 13:**2285–2289, 2002
29. Selby G: Parietal lobe syndromes. **Australas Ann Med 5:**89–100, 1956
30. Sergent J: Mapping the musical brain. **Human Brain Mapping 1:** 20–38, 1993
31. Sergent J, Zuck E, Terriah S, MacDonald B: Distributed neural network underlying musical sight-reading and keyboard performance. **Science 257:**106–109, 1992
32. Signoret JL, van Eeckhout P, Poncet M, Castaigne P: [Aphasia without amusia in a blind organist. Verbal alexia-agraphia without musical alexia-agraphia in braille]. **Rev Neurol (Paris) 143:** 172–181, 1987 (Fr)
33. Souques A, Baruk H: Autopsie d'un cas d'amusie (avec aphasie) chez un professeur de piano. **Rev Neurol (Paris) 4:**545–557, 1930
34. Stewart L, Henson R, Kampe K, Walsh V, Turner R, Frith U: Brain changes after learning to read and play music. **Neuroimage 20:**71–83, 2003
35. Taylor MD, Bernstein M: Awake craniotomy with brain mapping as the routine surgical approach to treating patients with supratentorial intraaxial tumors: a prospective trial of 200 cases. **J Neurosurg 90:**35–41, 1999

Manuscript submitted February 13, 2006.
Accepted September 28, 2006.
Address reprint requests to: Franck-Emmanuel Roux, M.D., Ph.D., Service de Neurochirurgie et Institut National de la Santé et de la Recherche Médicale 825, Hôpital Purpan, F-31059 Toulouse, France. email: franck.roux@club-internet.fr.