Music, Language, Modularity and the Brain

Peretz & Coltheart 2003
Friederici 2012
Peretz 2006
Peretz & Zatorre 2005

Peretz & Coltheart 2003

- Fodor 1983: *The Modularity of Mind*
- Typical characteristics of mental modules:
  - Rapidity of operation
  - Automaticity
  - Domain specificity
  - Informational encapsulation
  - Neural specificity
  - Innateness
- NH: For Fodor, the sensory systems are modules, plus language.
- NH: Is modular processing unconscious?

Peretz & Coltheart 2003

- Innateness isn't necessary:
  - Reading
- Fodor: informational encapsulation is necessary.
  - Information processing within a module is immune from influence by the "central system".
    - A large and slowly operating encyclopedic knowledge system involved in high-level cognitive operations, such as problem solving or belief evaluation.
    - NH: Is some of this conscious?
- P&C: Domain specificity is equally necessary.

Peretz & Coltheart 2003

- A module can be composed of smaller processing subsystems, each of which can also be referred to as a module.
- Music may be a module.
- The putative music module may possess the property of neural specificity (neuro-anatomical separability).
  - If so, then brain damage could affect musical abilities while sparing all other aspects of cognition (e.g. auditory processing of language).
  - Such people have been found.
    - Acquired and congenital amusia.
  - Perhaps music is affected in such people because it is a less practiced skill than language, and so it is more vulnerable.
    - But there are also cases of aphasia without amusia.

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- The proposed model shows the functional architecture of music processing that has been derived from case studies of specific music impairments in brain-damaged patients.
- A neurological anomaly can either damage a processing component (box) or interfere with the flow of information (arrow) between components.
- Each component represents a break-down pattern, giving each component the property of neural specificity.
- There are submodules within the system.

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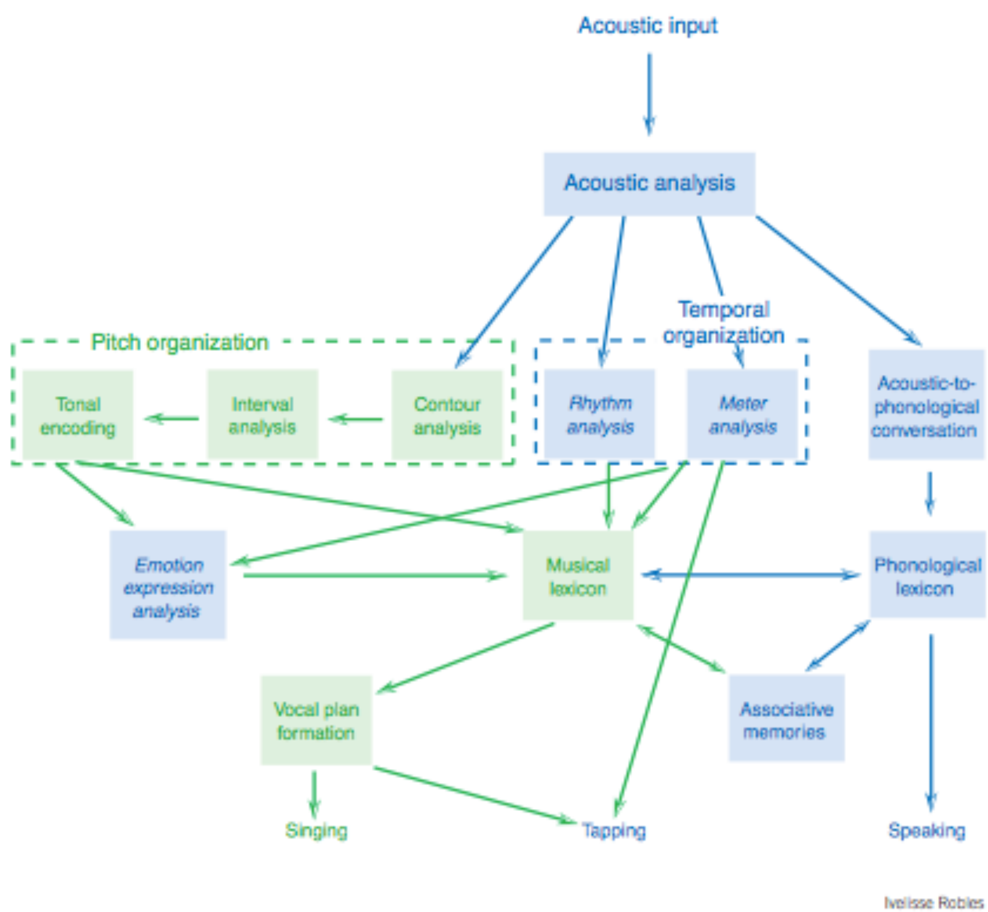
Figure 1 A modular model of music processing. Each box represents a processing component, and arrows represent pathways of information flow or communication between processing components. A neurological anomaly may either damage a processing component (box) or interfere with the flow of information between two boxes. All components whose domains appear to be specific to music are in green; others are in blue. There are three neurally individuated components in italics—rhythm analysis, meter analysis and emotion expression analysis—whose specificity to music is currently unknown. They are represented here in blue, but future work may provide evidence for representing them in green.



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- Some components are specific to music (tonal encoding of pitch), some are shared (contour analysis may be shared with speech intonation).
- Tonal encoding of pitch:
  - Automatic
  - Universal
    - Most musical scales use pitches of unequal spacing, 5-7 focal pitches.
  - Innate (infant studies)
    - Enhanced processing for scales with unequal pitches.
  - Neurally specific:
    - Some brain-damaged patients are no longer able to judge melodic closure properly and have severe problems with pitch memory.
    - Janata et al. 2002: Rostromedial prefrontal cortex

Language Processing: Friederici 2012

Opinion

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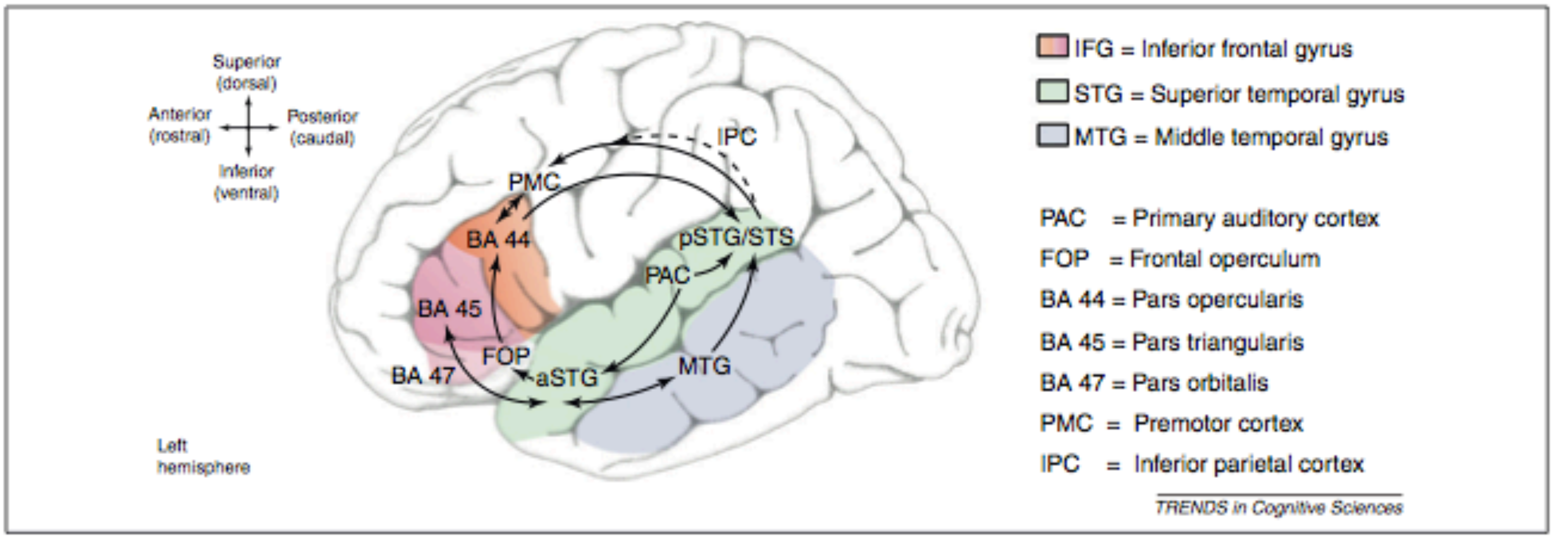


Figure 1. The cortical language circuit (schematic view of the left hemisphere). The major gyri involved in language processing are colorcoded. In the frontal cortex, four language-related regions are labeled: three cytoarchitectonically defined Brodmann [39] areas (BA 47, 45, 44), the premotor cortex (PMC) and the ventrally located frontal operculum (FOP). In the temporal and parietal cortex the following regions are labeled: the primary auditory cortex (PAC), the anterior (a) and posterior (p) portions of the superior temporal gyrus (STG) and sulcus (STS), the middle temporal gyrus (MTG) and the inferior parietal cortex (IPC). The solid black lines schematically indicate the direct pathways between these regions. The broken black line indicates an indirect connection between the pSTG/STS and the PMC mediated by the IPC. The arrows indicate the assumed major direction of the information flow between these regions. During auditory sentence comprehension, information flow starts from PAC and proceeds from there to the anterior STG and via ventral connections to the frontal cortex. Back-projections from BA 45 to anterior STG and MTG via ventral connections are assumed to support top-down processes in the semantic domain, and the dorsal back-projection from BA 44 to posterior STG/STS to subserve top-down processes relevant for the assignment of grammatical relations. The dorsal pathway from PAC via pSTG/STS to the PMC is assumed to support auditory-to-motor mapping. Furthermore, within the temporal cortex, anterior and posterior regions are connected via the inferior and middle longitudinal fasciculi, branches of which may allow information flow from and to the mid-MTG.

Language Processing: Friederici 2012

- "The cortical language circuit: from auditory perception to sentence comprehension". Trends in Cognitive Science, May 2012.
- Two dorsal pathways and two ventral pathways.
- Input is to the primary auditory cortex (PAC), bilaterally. Only the left hemisphere is shown here.
- One key area is the posterior STG (pSTG).
  - Is this Wernicke's area?

The temporal cortex: from auditory cortex to words and phrases: Friederici 2012

- Acoustic-phonological analysis, processing of phonemes:
  - left middle STG (lexical status recognized 50-80 ms), syntactic category error recognized (40-90 ms).
- A word's syntactic category enables the initial construction of syntactic phrases:
  - Anterior STG.
- Lexical-semantic access occurs fast:
  - 110-170 ms after word recognition.
  - N400 starts at 200 ms: Middle temporal gyrus (MTG)
- Sentential-level semantic processes seem to involve the anterior temporal lobe, posterior temporal cortex and angular gyrus.
- Anterior temporal lobe may be involved in integrating basic phrase structure with semantic combinatorics.

From temporal to frontal cortex: towards higher-order computation: Freiderici 2012

- aSTG and FOP (higher ventral) pathway feeds into higher-order structural aspects that establish grammatical relations (syntax).
  - Broca's area BA44 unpacks noncanonical word order, e.g. OSV order.
  - Posterior part of Broca's area BA45 handles displacement from subordinate positions.
- Higher level semantics—thematic relation computation—involves BA47 and anterior BA45: (lower ventral pathway)

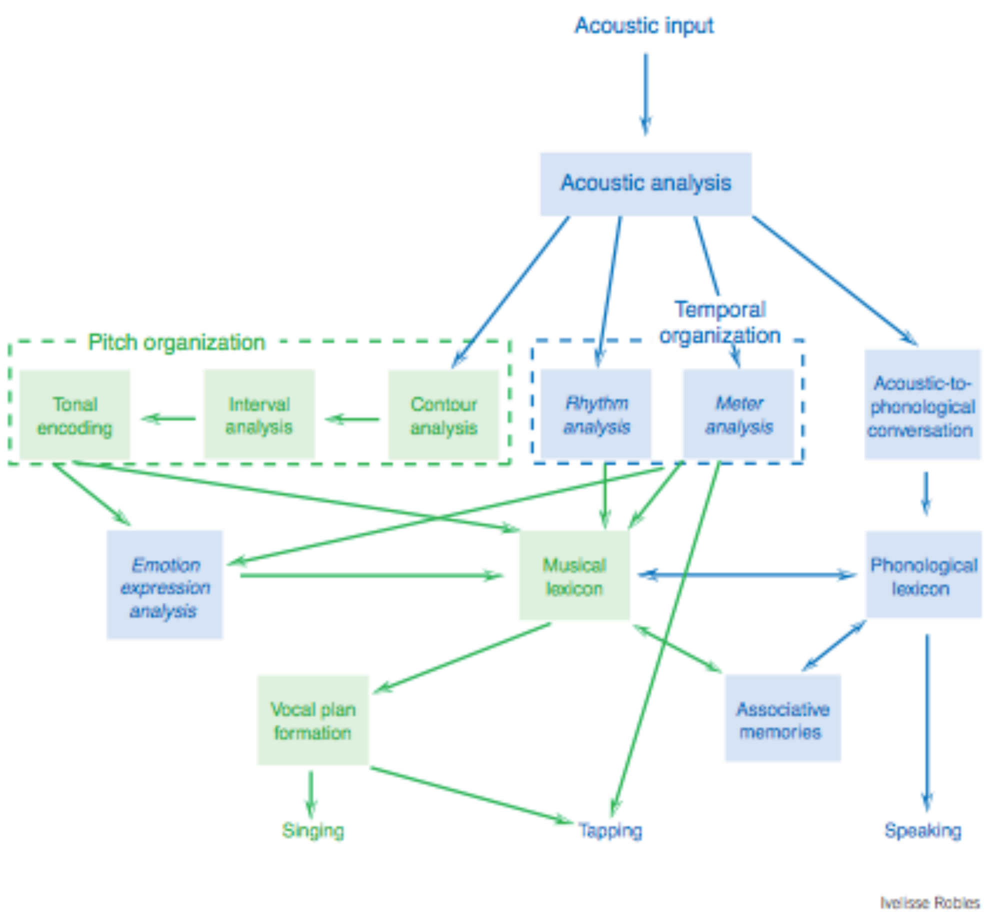
From inferior frontal cortex back to temporal cortex: Freiderici 2012

- Posterior STG (pSTG) is postulated to be the region of semantic-syntactic integration.
  - Two pathways could lead back to the pSTG: the bottom dorsal pathway and the bottom ventral pathway.
  - Syntactic working memory is in dorsal BA44 and is activated when sentences are structurally complex.
  - Phonological working memory is in the parietal cortex.
  - The bottom dorsal pathway passes back predictions e.g. that after three arguments a ditransitive verb should be encountered (verb-final language like German).

Pathways and functions: Friederici 2012

- Upper dorsal pathway connects the temporal cortex with the primary motor cortex (PMC)
  - Sensory-to-motor mapping in a bottom-up manner.
  - Present at birth.
- Lower dorsal pathway processes structurally complex sentences from the top-down.
  - Connection only develops as the brain matures.
- Upper ventral pathway also processes syntax, but syntactic phrase-structure building.
- Bottom ventral pathway mediates top-down controlled lexical-semantic access to the MTG and semantic predictions to the posterior temporal cortex.

Peretz & Coltheart 2003



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- The model takes as input any acoustic stimulus that can be attributed to a unique source, not just music.
- Output might be a representation of a song "Happy Birthday", which then enters music and language processing in parallel.
- Only the relevant modules will respond to relevant aspects of the stimulus.

Peretz & Coltheart 2003

- The musical input modules are organized into parallel pitch processing and temporal information processing units.
  - The "rhythm analysis" component deals with the segmentation of the ongoing sequence into temporal groups on the basis of durational values without regard to periodicity.
  - The "metrical analysis" component extracts an underlying temporal regularity of beat, corresponding to regular alternations between strong and weak beats
    - Feeds into a foot tapping output, which can be impaired in congenital amusia.

Peretz & Coltheart 2003

- Both the melodic and temporal pathways send their outputs to either the 'musical lexicon' or 'emotion expression analysis' component.
  - The musical lexicon contains representations of all the musical phrases one has been exposed to, and keeps a record of any new musical input.
    - Associative memories are evoked when the task is to name the tune or retrieve a related experience from memory.
  - The emotion expression analysis component takes as input mode (major, minor), and tempo (slow, fast), etc. allowing the listener to recognize and experience emotions evoked by the music.
    - It's not yet clear if this component is specific to music.
    - This feeds into the musical lexicon component, aiding in recognition.

Peretz 2006

- Neural systems which are domain-specific and localized do not have to innate.
  - Reading depends critically on phonological awareness and on the visual word form system
  - A left inferior temporal region specifically devoted to the processing of letter strings (Cohen et al. 2000).
- Innateness can be posited for a function or task without invoking specialized or localized mechanisms.
  - Trehub & Hannon 2006
  - Music perception is the product of general mechanisms operating in conjunction with an innate motivational disposition towards music.

Peretz 2006

- In contrast, Lerdahl & Jackendoff, Dowling, Peretz & Coltheart have proposed that music processing components, rely on domain specific mechanisms and specialized neural networks.
  - E.g. tonal encoding of pitch.
- Genetic basis for this:
  - Draina et al. 2001
  - 136 identical twins and 148 fraternal twins were required to detect out-of-key notes in popular melodies.
  - Performance was more similar between identical twins.
  - 70-80% heritability.
- Such strong evidence for the biological thesis of music cannot be made as forcefully for other music components.

Peretz 2006

- Domain specificity
  - Although "domain specificity" is typically used to refer to a faculty, there is no reason to exclude it from applying to a component.
  - A domain may be as broad as *auditory scene analysis* (which intervenes for all incoming sound) or as specific as *tonal encoding of pitch* (specific to music).
  - Domain-specificity can emerge through learning.
    - The learning may be guided by innate mechanisms.
    - It may also use general principles, e.g. extracting statistical regularities from the environment.
    - The input and output of the statistical computation may be domain-specific while the learning is not.
    - Once acquired, the functioning of the system may be modular.

Peretz 2006

- Domain specificity cont.
  - The fact that audi*tory scene analysis* and *auditory grouping* both use Gestalt principles such as pitch proximity, does not entail that their functioning is general-purpose and mediated by a single processing system
    - Visual and auditory scene analysis both obey Gestalt principles.
    - The input codes may transform general-purpose mechanisms into highly specialized ones.
      - Modularization is efficient
  - To what extent does music processing rely on dedicated mechanisms?

Peretz 2006

- Domain specificity cont.
  - Is only the tonality system dedicated to music?
    - Pinker 1997: the other components of music are parasitic on e.g. the language module.
  - But autistic individuals are more apt in music than in other domains, including language (Henton et al. 1998), and there are tone deaf individuals who are normal in language.
  - There are also cases of acquired amusia.
    - Double dissociations between music and language are convincing evidence for modularity.
    - Although double dissociations can be simulated in an artificial network that is built on a unitary system (Plaut 1995).
  - An impairment in tonal encoding of pitch may arise as a consequence of a lower-level deficiency, involving fine-grained pitch analysis or pitch direction extraction.
  - Rhythm disorders can occur independently from pitch disorders, but music specificity here is not yet known.

Table 1
Case reports of selective impairment and selective sparing in the auditory recognition of words, tunes, and other meaningful sounds (left panel) and in the production of notes, words, and intonation (right panel)

Reports	Input domains			Reports	Output domains			
					Singing		Speaking	
	Tunes	Words	Other familiar sounds		Notes	Words	Intonation	Words
Peretz et al. (1994) C.N. and G.L.	−	+	+	C.N. and G.L.	−	+	(+)	+
Peretz et al. (1997). I.R.	−	+	+	I.R.	−	+	(+)	+
Griffiths et al. (1997). H.V.	−	+	+	Schön et al. (2004). 1 case	−	+	(+)	+
Wilson and Pressing (1999). H.J.	−	+	+	Murayama et al. (2004) 1 case	−	+	(+)	+
Piccirilli et al. (2000). 1 case	−	+	+					
Steinke et al. (2001). K.B.	−	+	+					
Ayotte et al. (2002). 11 cases of congenital amusia	−	+	+ (+ voices)	11 cases of congenital amusia	−	+	(+)	+
Satoh et al. (2005). 1 case	−	+	+					
Laignel-Lavastine and Alajouanine (1921). 1 case	+	−	+	Hébert et al. (2003) CC	+	−		−
Godefroy et al. (1995). 1 case, during recovery	+	−	+	Peretz et al. (2004) GD	+	−		−
Mendez (2001). N.S.	+	−	+	Racette and Peretz (in press) 8 cases	+	−		−
Metz-Lutz and Dahl (1984). G.L.	+	−	−					
Takahashi et al. (1992). 1 case	+	−	−					
Yaqub et al. (1988). 1 case	+	−	−					

+, preserved; −, impaired; (+), preserved but not formally tested.

Peretz 2006

- Innateness
  - The FOXP2 gene
    - Half the KE family suffer from a speech and language disorder (Hurst et al 1990).
    - Three generations: half the children of affected individuals have the disorder and none of the children of unaffected members do.
    - A chance discovery of another individual with the disorder narrows it down to a mutation of a specific gene, FOXP2. (Lai et al 2001)
    - The disorder also affects oral movements.
    - Alcock et al 2000 tested nine affected members of the KE family and showed they were impaired in rhythm production and perception but not in melody processing.
    - Perhaps a deficit in sequential temporal processing.

Peretz 2006

- Innateness cont.
  - Congenital amusia, which often involves pitch but not rhythm deficits, also runs in families.
  - Thus, the available data are compatible with the idea that there are two innate factors guiding the acquisition of the musical capacity, with one related to temporal sequencing and the other, pitch sequencing.

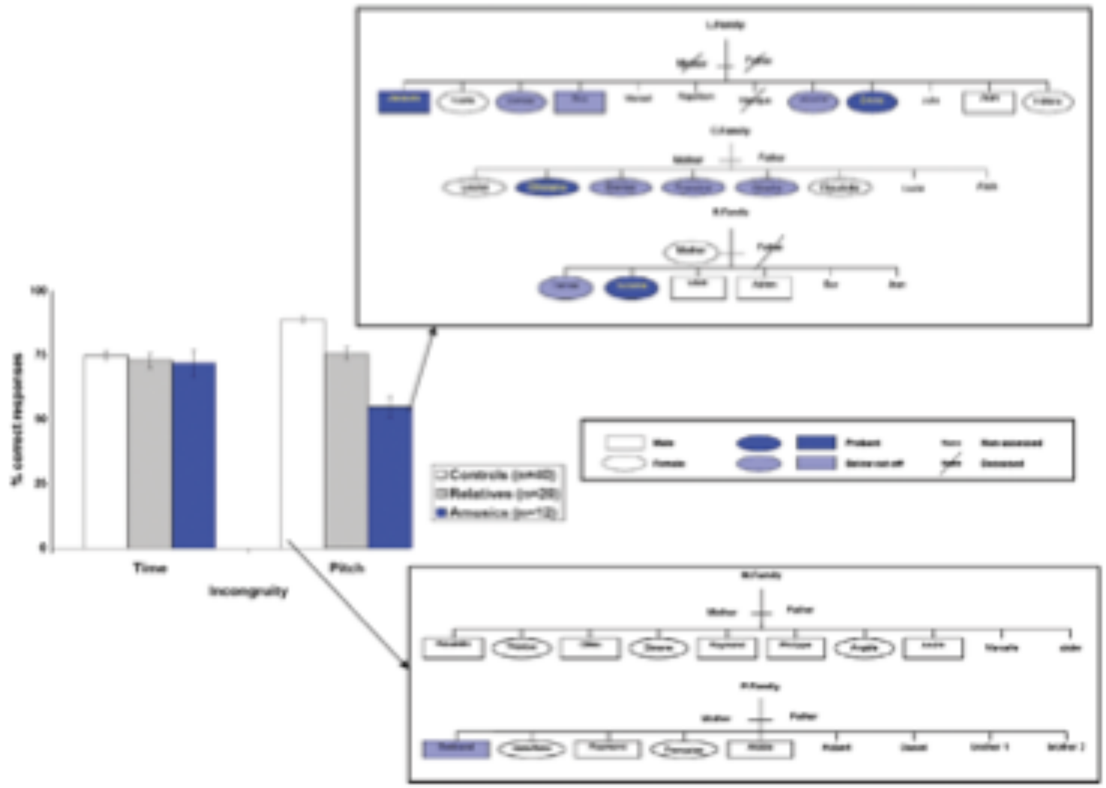


Fig. 2. Amusics and their first degree relatives were significantly impaired in the detection of a pitch anomaly in melodies as compared to their matched controls (see left graph). In contrast, all subjects performed similarly in the detection of time delays inserted in the same melodies. This pattern is supported by a significant interaction between Group and Condition ($F(2,69) = 20.45$, $p < .001$). As can be seen in the pedigree of three representative amusic (proband) families (top) and two representative control families (bottom), the presence of a musical pitch disorder runs in families; a pitch deficit corresponds to a score that lies 2 *SD* below the mean of the control group (below cut-off). Moreover, not all family members are affected, discarding an environmental factor as a plausible cause.

Peretz 2006

- Innateness cont.
  - Infants are predisposed to appreciate music
    - 6-9 month infants process consonant intervals better than dissonant ones and exhibit enhanced sensitivity to musical scales with unequal steps (Trehub et al. 1999).
    - Infants prefer music that is subject to an isochronous temporal pulse (Demany et al. 1977).
    - However, precocious abilities could be the result of formidable plasticity in the infant brain.
      - The human brain is thought to be born prematurely with little pre-wiring.
      - Simple exposure to music may create connections and networks.
      - Caregivers sing slowly, at a high pitch level, with exaggerated rhythm and in an emotionally engaging manner.
      - Infants prefer infant-directed singing to infant-directed speech.

Peretz 2006

- Innateness cont.
  - Infants are predisposed to appreciate music
    - Trehub & Hannon 2006: the propensity to listen to music may be innate.
      - Such a “music detector” system could be coupled with a general-purpose system that acquires musical rules through learning or experience.
      - Modularization might emerge later as the result of fine-tuning such mechanisms.
    - But such a learning approach can’t readily account for the preference for consonant intervals: octaves and perfect fifths; or for unequal scale steps.

Peretz 2006

- Brain localization
  - A domain-specific processor or module need not be confined to a focal neural network as opposed to a vastly distributed neural network.
    - There is no clear correspondence in neural terms for language modules (Hickok & Poeppel 2004).
    - A music module could be intermingled with networks devoted to the processing of other complex patterns, such as speech intonation.
      - But brain-damage shows some neuroanatomical isolability of music modules.
  - Music processing recruits a vast network of regions located in both hemispheres, with an overall right-sided asymmetry for pitch-based processing.

Peretz 2006

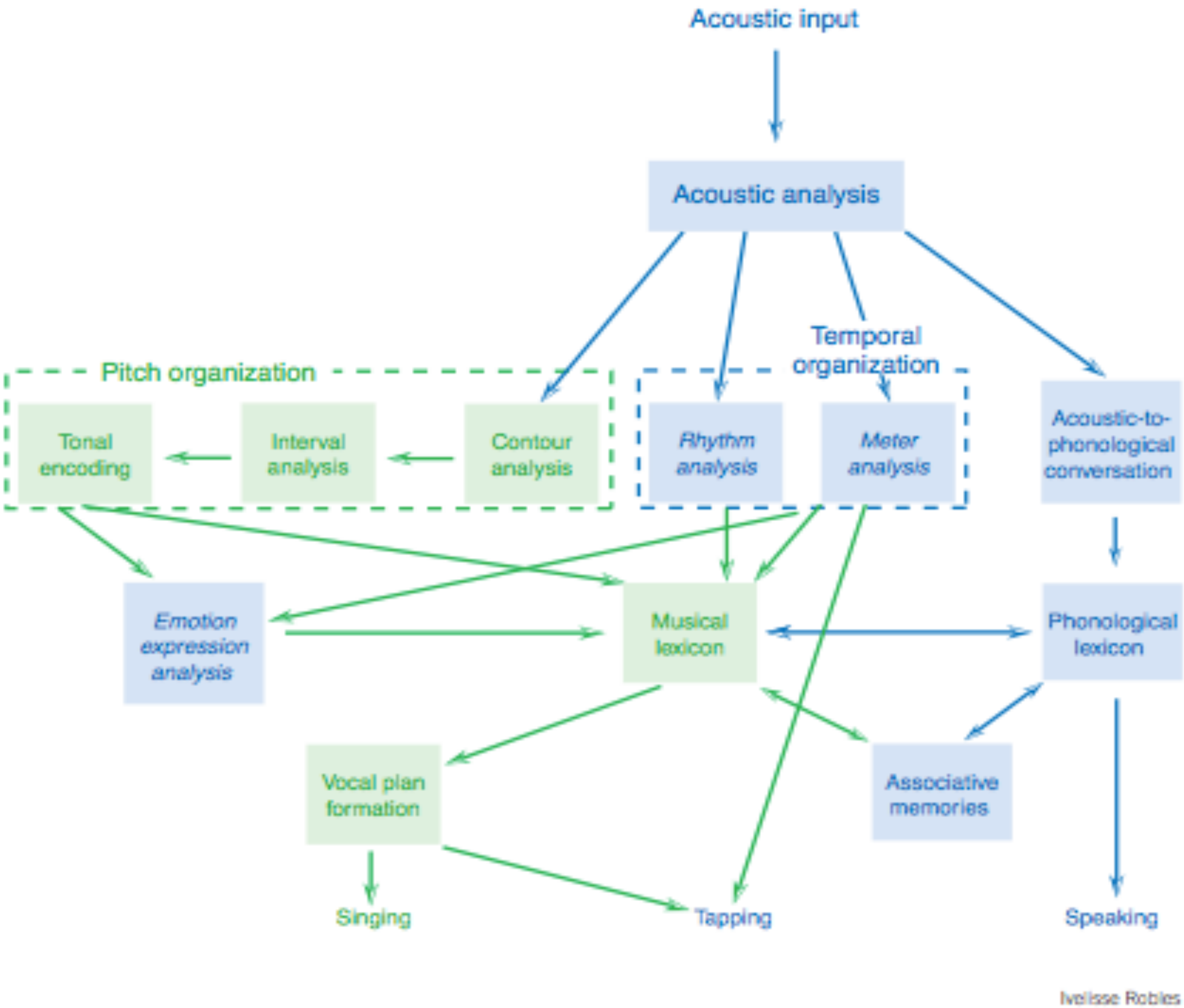
- Brain localization
  - Music and language processing seem to overlap.
    - Patel 2003, Koelsch et al 2004, etc.
    - But we should be cautious.
      - E.g. Broca's area is a vast brain region that can easily accommodate more than one distinct processing network, and activation in some studies is not limited to the left hemisphere.
    - As attempts for neural separability fail, we should become increasingly skeptical regarding the complete isolation of music processing from language processing.

Peretz 2006

- Brain localization
  - One would expect a pre-wired organization to exhibit consistency in brain localization.
  - Such a prediction is nontrivial in music because there is a wide variability of experience.
  - Musicians' brains are different.
    - The cortical representation of the digits of the left hand are larger for string players (Elbert et al. 1995).
    - Brain responses to piano tones are 25% larger In musicians (Pantev et al. 2003).
    - Early responses to pure tones and grey matter volume in part of Herschel's gyrus are 100% greater in musicians (Schneider et al. 2002).

Peretz 2006

- Brain localization
  - The brain system that underlies specialization for pitch processing may be fixed (probably innate).
  - Other brain systems involved in music might be more plastic within a time period (critical period).
  - And finally others may be plastic over an entire lifetime.



Acoustic input
Acoustic analysis
Temporal organization
Pitch organization
Tonal encoding
Interval analysis
Contour analysis
Rhythm analysis
Meter analysis
Acoustic-to-phonological conversation
Emotion expression analysis
Musical lexicon
Phonological lexicon
Vocal plan formation
Associative memories
Singing
Tapping
Speaking
Ivelisse Robles

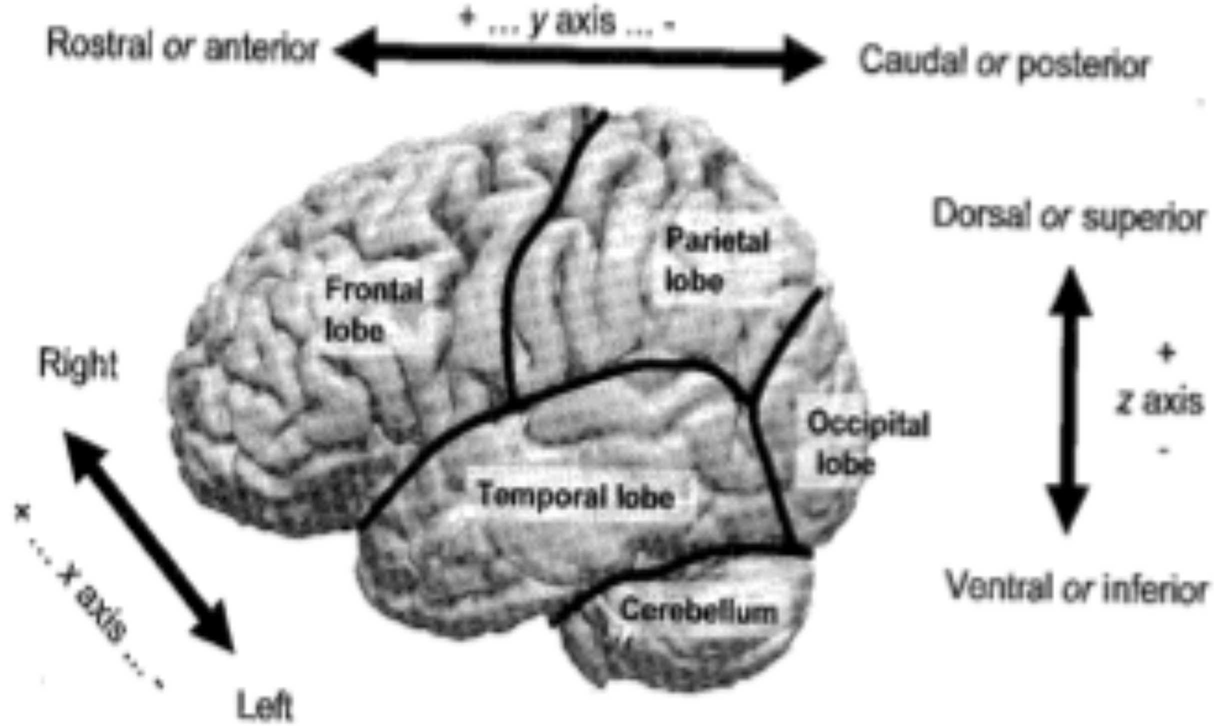


Figure 4.1 Lobes of the neocortex and the cerebellum, along with coordinate labels. The left hemisphere of author PQP's brain is shown.

Source: Brain image scans produced in collaboration with the Buffalo Neuroimaging Analysis Center (Robert Zivadinov, M.D., Ph.D., Jennifer L. Cox, Ph.D.) www.bnac.net. Used by permission from BNAC.

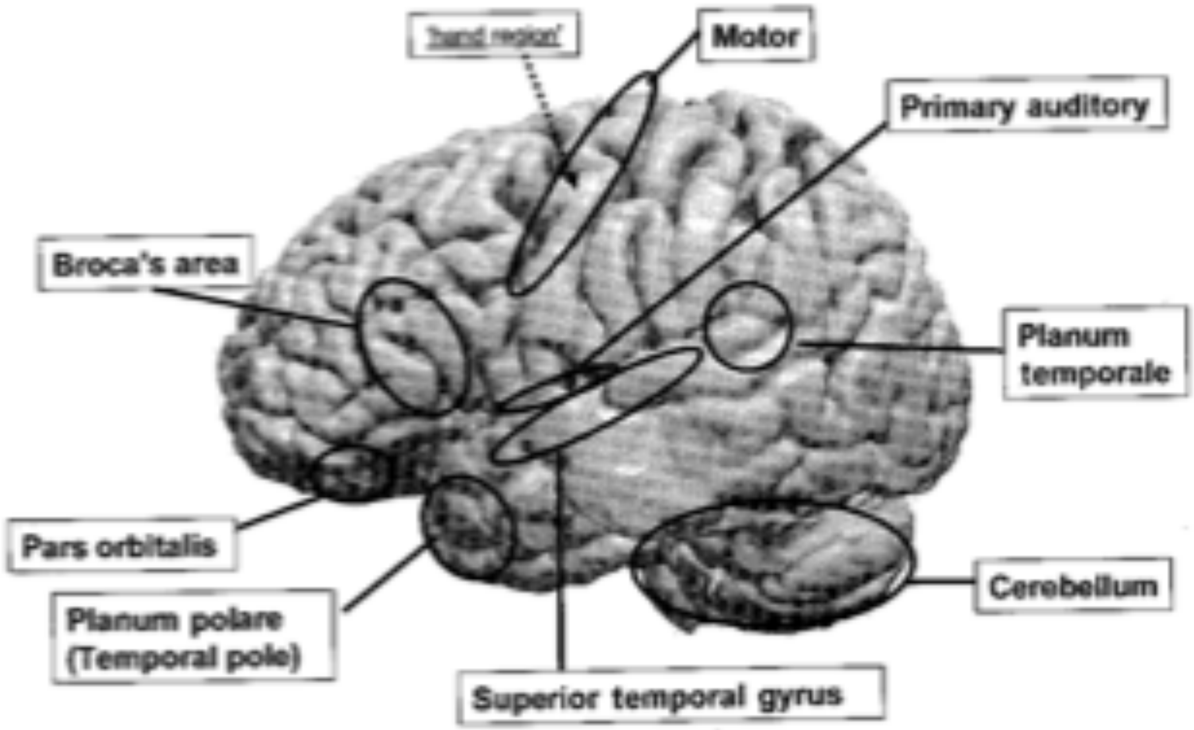


Figure 4.2 Surface regions of the brain associated with music. The left hemisphere of author PQP's brain is shown. Arrows are used to indicate regions on a more localized scale.

Source: Brain image scans produced in collaboration with the Buffalo Neuroimaging Analysis Center (Robert Zivadinov, M.D., Ph.D., Jennifer L. Cox, Ph.D.) www.bnac.net. Used by permission from BNAC.

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- Pitch relations
  - The data are quite consistent in implicating the **right secondary auditory cortex** region in operations related to processing relationships between pitch elements as they change over time, especially if the pitch changes are small.
  - When listeners rely on contour representation to discriminate melodies, the **right superior temporal gyrus** plays a critical role.
  - When contour cues are not available and interval information is required, both the **right and left temporal** structures appear to be involved.
  - The evidence points to the existence of neural networks that are specialized for the processing of scale structure in melodies. Their localization, however, remains to be determined.
  - The data point **to bilateral** involvement of the **inferior frontal regions (Broca's area**) in detecting deviations from harmonic expectancies.

Peretz & Zatorre 2005

- Time relations
  - Subjects more easily tapped a rhythmic pattern with their right hand and the beat with their left hand than the other way around. These findings suggest that the **right** hemisphere better handles meter, whereas grouping would rely essentially on the **left**.
  - Two brain-damaged patients, after lesions of the **right temporal auditory cortex**, could no longer tap the beat or generate a steady pulse.
  - Patients fail on meter evaluation after a **right**-sided lesion of the **anterior** part of the **superior temporal gyru**s.
  - Imaging studies converge on the conclusion that a supramodal **cerebellar** timing system is involved in processing temporally organized events. Other fMRI studies have produced evidence for the possible involvement of the **basal ganglia** in both motor and perceptual timing.
  - Finally, several studies have pointed to the involvement **of motor cortical areas** in rhythm perception and production, including the **supplementary motor area, premotor cortex, and parietal cortex**.

Peretz & Zatorre 2005

- Memory
  - Lesion studies focusing on working memory for pitch materials have implicated the **right auditory cortex**.
  - Working memory for tones engages interactions **between frontal cortical and posterior temporal areas**, as is true for other domains.
  - Working memory for pitch may be seen as a specialized subsystem within the framework of general working memory.
  - A lesion to **either medial temporal region** led to initial difficulties in learning the melodies; after **right-sided lesions**, retention of melodies was affected more severely and selectively over time.
  - Difficulties in recognizing familiar melodies tend to occur after a surgery to **either superior temporal region**. Moreover, the participation of **left inferior temporal and frontal areas** for recognizing familiar music has been pointed out in neuroimaging studies.
  - Retrieval processes from long-term representations, such as might occur when generating [through imagery] a familiar tune, tend to engage **inferior frontal regions**.

Peretz & Zatorre 2005

- Emotion
  - Recognition of the emotional tone in music can be spared by brain damage while recognition of music identity is impaired, indicating that emotion recognition may rely on perceptual determinants that play little role in identity recognition.
  - While people experienced musical chills, cerebral blood flow changes occurred in several brain areas, including the **dorsal midbrain, ventral striatum** (which contains the nucleus accumbens), **insula**, and **orbitofrontal cortex**.
  - Some of these regions have previously been implicated in response to highly rewarding or motivationally important stimuli, including food and drugs of abuse. Thus, under certain circumstances, music can access neural substrates that are primarily associated with biologically significant stimuli. Whether music is unique in this respect remains to be seen; it may be one of a class of human constructs that elicit pleasure by co-opting ancient neural systems via inputs from neocortex.