The Neural Locus of Temporal Structure and Expectancies in Music: Evidence From Functional Neuroimaging At 3 Tesla

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The neuroanatomical correlates of temporal structure and expectancies in music were investigated using a unique stimulus manipulation involving scrambled music. The experiment compared brain responses (using functional magnetic resonance imaging) while participants listened to classical music and scrambled versions of that same music. The scrambled versions disrupted musical structure while holding low-level musical attributes constant, including such psychoacoustic parameters as pitch, loudness, and timbre. Comparing music to its scrambled counterpart, we found focal activation in the pars orbitalis region (Brodmann Area 47) of the left inferior frontal cortex, a region that has been previously closely associated with the processing of linguistic structure in spoken and signed language, and additional activation in the right hemisphere homologue of that area. We speculate that this particular region of inferior frontal cortex may be more generally responsible for processing fine-structured stimuli that evolve over time, not merely those that are linguistic.

ONE of the cornerstones of music theory—as well as theories of music cognition—is that music contains structure: that which distinguishes music from a merely random collection of sounds is that musical elements occur in a specific order. It is an axiom of music theories that if one were to reorder the musical elements of a composition it would lose its identity (Lerdahl, 2001; Patel, 2003), and this is consistent with formal theories of

structure in nonmusical domains (Garner, 1974). In many media (such as visual art), structure is manifested over space; in music, the structure is manifested over *time.* The temporal nature of music leads to expectancies as the music unfolds; these expectancies are an inherently temporal construct involving the future, and they create a predisposition to perceive a particular event or member of a defined class of events in the future. Expectancies involve both anticipations about *when* something will occur in the future and *what* is expected (Barnes & Jones, 2000). The quality that exists when a sequence of tones appears to be connected, or coherent musically, has been termed *temporal coherence* in music (Deutsch, 1999; Jones & Pfordresher, 1997) and reflects the spectral-temporal continuity present in an organized sequence of tones.

Attendant to these theories is that musical structure is hierarchical and follows syntactic principles (Cooper & Meyer, 1960; Lerdahl, 2001; West, Howell, & Cross, 1985). It is important to clarify terms and to distinguish static or dominance hierarchies (such as tonal relations) from nested dynamic hierarchies (such as temporal hierarchies for rhythm) in music (Jones, 1981). The *static hierarchy* of tonal relations is evidenced in the tendency for musical compositions to be organized around one central tone and a hierarchy of auxiliary tones (Krumhansl, 1990; Lerdahl, 2001); the tonic and tones closely related to it are more likely to mark the ends of phrases than are other tones. Meter and rhythm, on the other hand, are *dynamic,* based on *time markers* in music (which are often tonally salient elements) and these time spans can be nested, hierarchically, within one another. Temporal hierarchies can be considered a global attribute of music (rather than a local one); they constitute a holistic characteristic of a composition because they require that the listener interpret the whole piece or phrase, not just isolated, local elements (Schulkind, Posner & Rubin, 2003). Syntax in both language and music refers not just to these hierarchies, but to rules and conventions that contribute to structure in both domains (Cooper & Meyer, 1960; Lerdahl, 2001; West et al., 1985).

Patel (2003) introduced the "Shared Syntactic Integration Resource Hypothesis" (SSIRH) in which he posited that syntax in language and music share a common set of neural processes instantiated in frontal brain areas. SSIRH is based, in part, on findings from a number of studies implicating frontal regions in the processing of harmonic structure (Janata, et al., 2002; Tillmann, Janata, & Bharucha, 2003) and in particular, the processing of harmonic anomalies (Koelsch et al., 2002; Maess, Koelsch, Gunter, & Friederici, 2001). In the latter paradigm, participants are presented with sequences of music (typically cadences) that either resolve in an ordinary fashion or in an unexpected fashion. In addition to tapping into syntactic processing, these studies also elicit sudden and automatic shifts of attention that result from unexpected sounds (*temporal capture*,

Barnes & Jones, 2000) and thus engage a number of ancillary cognitive operations not directly related to the processing of whole-piece dynamic processes, or to global musical syntax. These ancillary processes include surprise, detection of tonal dissonance, and shifting or reorienting attentional focus from one tonal center to another. Consequently, we sought to create an alternative paradigm that would eliminate these ancillary processes and allow us to examine the neural substrates of long-term musical expectancy.

An additional goal was to test the SSIRH more directly by devising a test that would disrupt musical syntax in a global (rather than punctuated local) fashion as has been previously studied. Structure exists in music when one can differentiate an ordered sequence from a random sequence of musical events (Patel, 2003). Thus, in the present experiment we randomized ("scrambled") musical excerpts within pieces of music in order to disrupt holistic musical structure (or syntax) and to examine those neural structures that are involved in the processing of musical stimuli. To reference equivalent terminology, we disrupted temporal contingencies among elements, violating all those features that Schulkind et al. (2003) termed *holistic*: tonal functions, contour patterns, metrical accents/joint accent structure (Jones & Boltz, 1989; Jones & Pfordresher, 1997), rhythmic phrases, and phrase boundaries. If the SSIRH is correct, we would expect to find greater activation (as indexed by the Blood Oxygenation Level Dependent Signal, or BOLD) during music listening compared with nonsense music listening in frontal brain regions previously associated with the processing of syntax in language in mid-ventrolateral prefrontal cortex (Petrides, 2000; Tallal, et al., 1996; Temple, et al., 2000), specifically in Brodmann Area 47 (Dapretto & Bookheimer, 1999; Petitto, et al., 2000; Poldrack et al., 1999). (For a brief introduction to functional magnetic resonance imaging [fMRI] methods, see the box on the following page.)

Methods

Full details of the methods are contained in Levitin and Menon (2003), including an extensive description of the fMRI methodology. Only an abbreviated summary is provided here.

SUBJECTS

Subjects were 13 right-handed and normal-hearing adults; age ranged from 19.4 to 23.6 years, 7 females and 6 males, all nonmusicians (as in Maess et al., 2001).

STIMULI

The stimuli consisted of digitized sound files (22,050 sampling rate, 16-bit mono) taken from the first 23 s of compact disc recordings of standard pieces in the classical repertoire (23 s create blocks of optimal size for the fMRI analysis). Scrambled versions were created

Tutorial on fMRI Methods

Functional magnetic resonance imaging (fMRI) studies are based on the fact that the level of oxygen changes during mental activity. Neurons that are active change their own local blood supply, increasing oxygen more than is actually used and leading to an increase in hemoglobin. The presence of hemoglobin (which has slightly magnetic properties) can be tracked by a strong magnetic field (which is what an fMRI machine is). We can localize the areas of the brain that are active by tracing the level of oxygenation of the blood with MRI. Because of hemodynamic lag—the amount of time it takes for local blood oxygen levels to increase—the temporal resolution of fMRI is limited to several (4 to 6) seconds. In contrast, electroencephalograpy (EEG, or its component responses referred to as ERPs) and magnetoencephalography (MEG) have a temporal resolution of milliseconds. An advantage of fMRI over these other methods is its spatial resolution, which can be an order of magnitude better, allowing researchers to pinpoint *where* in the brain an operation is occurring, with a resolution approaching 1 mm. According to current medical knowledge, MRI is harmless to the patient, using only magnetic fields and nonionizing radiation in the radio frequency range.

The standard method in functional neuroimaging research is known as the subtraction paradigm. If brain regions are activated equally, or not at all, during two experimental conditions, this activation will cancel out in the subtraction of one from the other (referred to in the general case of A – B). Typically, researchers use an experimental condition and a baseline condition that controls for all operations (e.g., sensory and motor), except the one operation of interest. If one region responds more strongly in the experimental condition, compared with the baseline condition, it is said to be activated during the task, and the subtraction will yield signal changes that can then be tested for significance. If a region is activated more during the baseline task than during the experimental task, it is referred to as deactivation. Deactivation is a well-documented phenomenon, occurring most obviously in cases in which the brain must attenuate responses to accomplish a certain task.

It is important to note that in neuroimaging studies one is not studying the amount or extent of activation in the brain for one task only. Because the brain is normally occupied with a number of tasks, including the control and maintenance of homeostasis, respiration, circulation, and so on, as well as random and spontaneous thoughts, a snapshot of blood flow for a single task would yield all sorts of activation that are not directly of interest. The subtraction paradigm, first introduced by Posner and colleagues to neuroimaging, allows us to focus our analysis on brain regions that are active during a particular task or operation of interest.

Daniel J. Levitin & Vinod Menon

by dividing the 23-s normal musical excerpts into 250–350 ms variable-sized pieces, with the window size selected randomly within this interval. The pieces were then permuted using a random number generator and concatenated with a 30-ms linear cross-fade between excerpts. The MatLab program used to conduct the scrambling is available from the first author. The stimuli used are listed in the on-line supplementary materials in the appendix.[1]

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1. Supplementary materials are available on line at http://www.psych.mcgill.ca/labs/levitin/research/musicsamples.html.
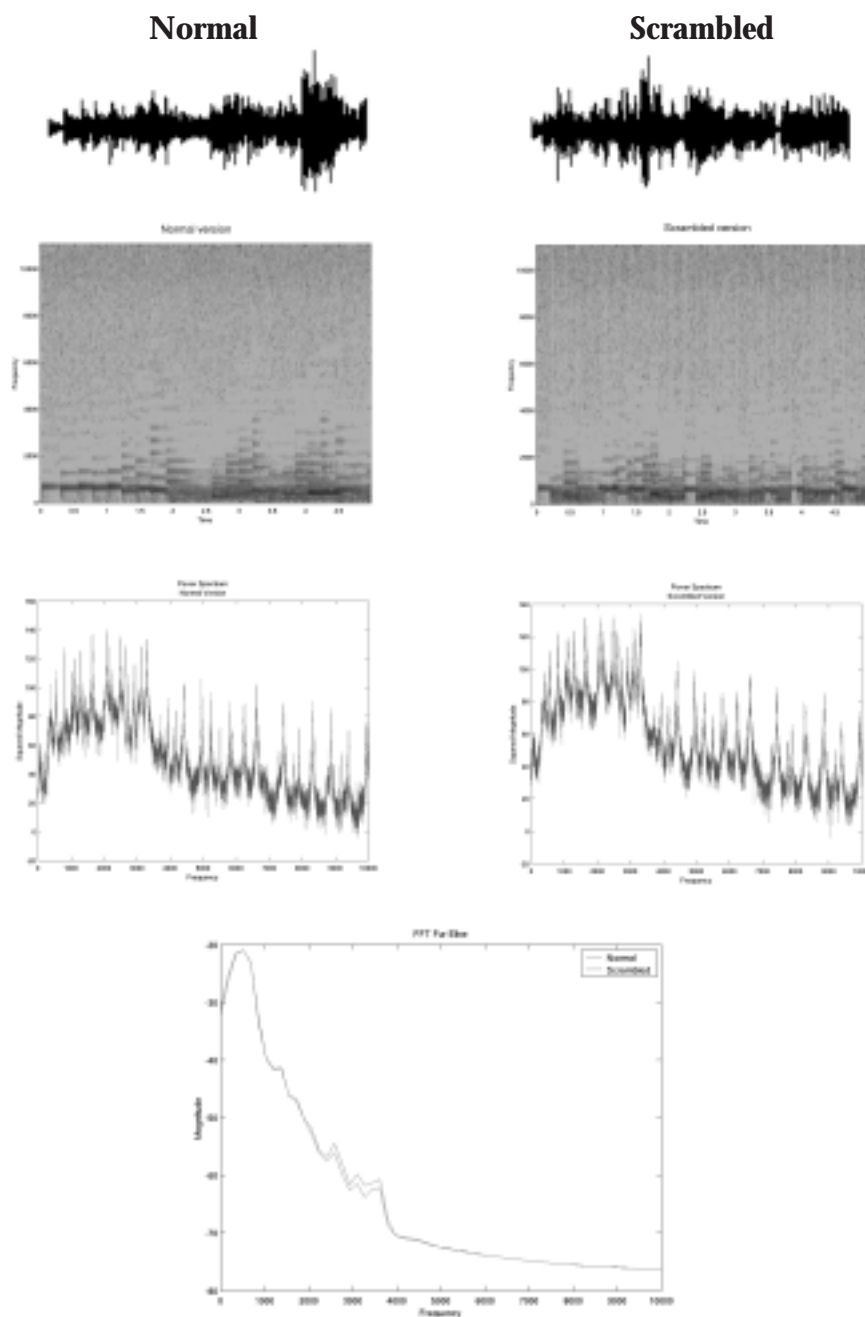
Fig. 1. Normal (left) vs. scrambled music (right) stimulus comparisons for the first 5 seconds of a typical musical piece (*Für Elise*) used in the present experiment. Top panel: amplitude vs. time. Second panel: Spectrogram. Third panel: Power spectrum. Bottom: Fast Fourier transform. The stimuli are spectrally equivalent and contain the same power over the duration of the excerpt presented. Color versions of these figures can be seen on-line at: http://www.psych.mcgill.ca/labs/levitin/research/musicsamples.html.

The differences between the control and the experimental conditions were as follows. Both retain, over the course of the 23-s excerpt, the same distribution of pitch and loudness (this must logically be true, because elements were simply reordered) and the same spectral information (as shown in Figure 1). Fast Fourier transforms (FFTs) between the normal and scrambled versions correlated significantly (Pearson's $r = .99$, $p < .001$ for all selections). Subjects listened to the sounds at a comfortable listening level over headphones employing a custom-built, magnet-compatible pneumatic audio delivery system. Pilot testing with a separate group of six participants established that the stimuli were equally matched for loudness.

fMRI ACQUISITION

Images were acquired on the 3T GE Signa scanner at the Lucas Imaging Center (Stanford University Medical School) using a standard GE whole head coil; 28 axial slices (4.0 mm thick, 0.5-mm skip) parallel to the ACPC line and covering the whole brain were imaged with a temporal resolution of 2 s using a T2*-weighted gradient echo spiral pulse sequence.

Results

We analyzed fMRI activation for the normal music versus the scrambled music conditions: the difference between these two conditions (Normal – Scrambled) should index neural processes associated with the perception of musical structure, but not with any features the two conditions had in common with one another. Comparing music and scrambled music in fact revealed *no* differential activation in primary or secondary auditory cortices, serving as a validation that the two conditions were well matched for low-level acoustical features believed to be processed in these structures, such as loudness, pitch, and timbre. As hypothesized, we found significant ($p < .01$, corrected) activation in the *pars orbitalis* region of prefrontal cortex (Brodmann Area 47) and the adjoining *anterior insula* as well as their right hemisphere homologues. (Color figures showing coronal sections of significant brain activations can be seen on-line at: http://www.psych.mcgill.ca/labs/levitin/research/musicsamples.html.) The right hemisphere activation was less extensive than activation in the left hemisphere; activation there was primarily confined to the posterior pars orbitalis section of the inferior frontal cortex (Brodmann Area 47), immediately adjoining the anterior insula. In addition, we found significant ($p < .01$, corrected) activation in the anterior cingulate cortex, the nucleus accumbens, brainstem, and the posterior vermis (see Table 1 for a complete list of activations and their Talairach coordinates). We also examined brain areas that showed greater activation in the scrambled, compared with normal, music condition (Color figures showing coronal sections of significant brain activations can be seen on-line at: http://www.psych.mcgill.ca/labs/levitin/research/musicsamples.html), and no activation was observed in either the left or the right prefrontal cortex (Table 2).

TABLE 1
**Brain Regions That Showed Significant Activation During Normal,
Compared With Scrambled Music**

Regions	*P* (corrected)	No. of Voxels	Maximum *Z* Score	Peak Talairach Coordinates (mm)
Left inferior frontal cortex, pars orbitalis (Brodmann Area 47) and adjoining insula	.019	100	3.70	-48 16 -6
Right inferior frontal cortex, pars orbitalis (Brodmann Area 47), anterior insular cortex	.010	110	3.15	44 16 -8
Anterior cingulate cortex (Brodmann Area 24)	<.007	116	3.88	10 22 32
Nucleus accumbens	< .001	194	4.61	-4 2 0
Brainstem	.040	89	4.00	-8 -26 -14
Posterior vermis/brainstem	<.001	245	3.97	6 -46 -40

NOTE—Six significant clusters of activation were found ($p < .01$ height, $p < .05$ extent). For each cluster, the brain region, significance level, number of activated voxels, maximum *Z* score, and location of peak in Talairach coordinates are shown.

One might argue that our results were an artifact of the nonscrambled music sounding somewhat familiar and the scrambled music being unfamiliar. That is, the activations we observed may have been due to differing cognitive functions invoked due to familiarity. To address this possibility, we presented participants with both familiar and unfamiliar selections (confirmed individually by each participant), unscrambled. A direct statistical comparison of these conditions revealed no differences in activation in Brodmann Area 47 or any other prefrontal regions, confirming that familiarity was not a confound for the prefrontal activations.

One might argue that a confound in our experimental design could have emerged if the normal and scrambled music differed in the salience of the tactus, that is, the pulse or beat to which one might tap one's feet

TABLE 2
**Brain Regions That Showed Significant Activation During Scrambled,
Compared With Normal Music**

Regions	*P* (corrected)	No. of Voxels	Maximum *Z* Score	Peak Talairach Coordinates (mm)
Right superior parietal lobule, intraparietal sulcus (Brodmann Area 7), posterior cingulate (Brodmann Area 23), precuneus (Brodmann Area 19)	< .001	1118	4.82	16 -68 40
Left inferior temporal gyrus, inferior occipital gyrus (Brodmann Area 37)	< .001	207	4.27	-52 -60 -10
Left superior parietal lobule, intraparietal sulcus (Brodmann Area 7), angular gyrus (Brodmann Area 39)	.003	132	3.64	-34 -76 36
Right middle occipital gyrus (Brodmann Area 19)	< .001	199	3.56	34 -86 18

NOTE—Five significant clusters of activation were found ($p < .01$ height, $p < .05$ extent). For each cluster, the brain region, significance level, number of activated voxels, maximum *Z* score, and location of peak in Talairach coordinates are shown.

(or at least the feet in one's mind). To counter this, we ran a control condition in which four participants tapped their feet to the normal and scrambled versions of two different pieces chosen at random from the stimulus set. The scrambled versions were presented first so as not to bias the participants. We calculated the percent coefficient of variation (cv) in each case and compared them statistically (the variability is the appropriate measure because mean tapping may be different across the examples, and it is the steadiness of pulse that is of interest). The results were: *William Tell Overture*: cv = 3.34 (normal) and 4.55 (scrambled), $z = .45$, $p \sim .66$ (*n.s.*); *Eine Kleine Nachtmusic*: cv = 4.54 (normal) and 4.18 (scrambled), $z = .13$, $p \sim .90$ (*n.s.*). Because the scrambled selections logically contained a larger distribution of short notes than the unscrambled, as an additional test, we performed an analysis of note length distributions between the two versions for two songs chosen at random. This difference was not significant (by Wald-Wolfowitz runs test, $p \sim .10$ for both comparisons). One piece of converging neural evidence that the strength of pulse was matched across conditions was the lack of cerebellar activation.

Discussion

Our subjects listened with focused attention to music from the standard classical repertoire, and we compared brain activations in this condition with activations when listening to scrambled versions of those same musical pieces. The objective of presenting scrambled music was to break temporal structure; the comparison condition consisted of "nonmusical music," balanced for low-level factors. Previous investigations of musical structure have disrupted musical expectations by introducing unexpected chords, and consequently these manipulations examined only a more narrow and local notion of musical structure and expectation, and involved cognitive operations related to surprise, tonal dissonance, and the shifting of attentional focus to an incongruity. Our findings of no differential activation in the auditory cortex confirmed that the two conditions in the present experiment were well matched for low-level acoustical features. We hypothesized that we would obtain significant activation in the prefrontal cortex, in particular in Brodmann Area 47, if this region was involved in the processing of temporal coherence in music. This is in fact what we found, and is consistent with Patel's (2003) SSIRH that musical and linguistic syntax share common neural substrates for their processing.

Compared with normal music, scrambled music showed greater activation in the posterior cingulate cortex, the precuneus, cuneus, superior and middle occipital gyrus, and the inferior temporal gyrus. It is unlikely that activation in these regions directly reflects processing of scrambled music.

First, many of these regions are involved in various aspects of visual processing, and they are strongly "deactivated" in response to auditory stimuli (Laurienti et al., 2002). Although the auditory stimuli in our study were closely matched, it is likely that the two types of stimuli evoke different levels of "deactivation" for reasons that are not entirely clear at this time.

Our finding is consistent with a large number of studies linking the frontal cortex to semantic processing of spoken language (Bokde, Tagamets, Friedman, & Horwitz, 2001; Dapretto & Bookheimer, 1999; Demb et al., 1995; Ni et al., 2000; Poldrack et al., 1999; Roskies, Fiez, Balota, Raichle, & Petersen, 2001) and signed languages (Neville et al., 1998; Petitto et al., 2000), with a study associating activation of Brodmann Area 47 to discrimination of musical meter by nonmusicians (Parsons, 2001) and with research implicating the region near Brodmann Area 47 in dynamic auditory processing (Poldrack et al., 1999). The present study provides regional specificity to claims that there exists a unique cognitive system dedicated to the processing of syntactic structure (Caplan, 1995) and that prefrontal cortex may be central to dynamic prediction (Huettel, Mack, & McCarthy, 2002).

Whereas we found activation in BA47 when normal music was compared with scrambled music, other studies found significant activation in the same regions in response to linguistic stimuli containing punctuated incongruencies compared with normal music (Tillmann et al., 2003) or speech (Dapretto & Bookheimer, 1999; Ni et al, 2000, Experiment 1). If Brodmann Area 47 is involved in processing *structure*, why do we find activation when structure is intact, and other studies find activation when it is violated? One possible explanation is that these regions near Brodmann Area 47 may show a very high level of activation to punctuated incongruency, a moderate level of activation to intact structure (accounting for some of the musical and linguistic findings, Tillmann et al., 2003), and a low level of activation to material that utterly lacks structure (accounting for our present finding). In this view, Brodmann Area 47 might comprise a *structure tracker* that, in the face of a structural violation, recruits additional resources in an attempt to resolve the incongruity and continue tracking. Material that utterly lacks structure would fail to activate the tracker at all because there is nothing to track. The present study goes further than previous studies by showing that it is not only punctuated deviation that this region detects, but aspects of long-range structure (which previous designs could not tap into). Studies underway in our laboratories are exploring both these aspects of expectancy violation in language and music, using a within-subjects design.

Previous research has implicated the cerebellar vermis in music listening (Levitin et al., 2003), which we attribute along with the activation of the nucleus accumbens to the emotional component of listening to mean-

ingful music (Blood, Zatorre, Bermudez, & Evans, 1999; Schmahmann, 1997). These activations are presumably mediated by major connections linking the prefrontal cortex with the basal ganglia and the cerebellar vermis (Schmahmann, 1997), and they are consistent with the notion that a region in the right cerebellum may be functionally related to regions in the left inferior frontal cortex for semantic processing (Roskies et al., 2001), thus serving to link the cognitive and emotional aspects of music. Taken together, our findings and those of Griffiths, Uppenkamp, Johnsrude, Josephs, and Patterson (2001) suggest the involvement of subcortical auditory regions in the processing of temporal regularities in music.

In a study of musical imagery for familiar songs, and the processing of components associated with retrieval of songs from memory (Halpern & Zatorre, 1999), both operations activated Brodmann Area 47 (right hemisphere only) and musical imagery activated Brodmann Area 44 (left). When imagery involved "semantic retrieval" (here the authors are referring to semantic memory vs. episodic memory, not to the notion of semantic meaning of the musical piece), they found activation in Broca's area (left Brodmann Area 44). Our findings are consistent with these. Whereas those authors interpreted these findings as indicating involvement of Area 47 in memory, we believe in light of the current findings that their activation resulted from the structural aspects of the musical content.

According to theories of musical aesthetics, music does not represent specific, verbalizable emotions, such as jealousy or fear (Cooper & Meyer, 1960; Meyer, 1956). Rather, music represents the dynamic form of emotion, not the static nor specific content of emotional life (Langer, 1951). This conveying of emotion is the essence of musical semantics and depends on schemas and structure (Meyer, 1956). Almost without exception, theories of musical meaning are, in fact, theories of musical structure and its temporal coherence (Cooper & Meyer, 1960; Lerdahl & Jackendoff, 1971; West et al., 1985). Meaning itself, in a general sense, has been defined as the coordination of schemas and structure (Akmajian, Demers, Farmer, & Harnish, 1990; Bregman, 1977), the building of a consistent description based on rules that define internal consistency. Understanding music depends on generating expectancies—at least implicitly—and confirming to what degree those expectancies were met or violated (Jones & Boltz, 1989; Narmour, 1991). We believe that a large body of evidence is now converging to suggest that Brodmann Area 47 and the adjoining anterior insula constitute a modality-independent brain area that organizes structural units in the perceptual stream to create larger, meaningful representation. That is, they may be part of a neural network for perceptual organization, obeying the rules of how objects in the distal world "go together" when they are manifested as patterns unfolding in a structured way over time. The processing of structure (and per-

haps meaning) in music, may thus involve many of the same neural correlates as the processing of structure and meaning in other domains.[2]

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2. The present report comprises an extension and reanalysis of work originally published in Levitin and Menon (2003), including new data, and is done so with permission of Elsevier, Inc. Space limitations dictated that we dramatically abbreviate the methods section and, regrettably, many relevant citations. More complete information and references are contained in that report.

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Appendix: On-Line Supplementary Materials

MUSICAL STIMULI EMPLOYED

Standard pieces from the classical repertoire were selected on the basis of pilot testing. Using a separate group of 12 participants drawn from the same pool as our experimental participants, we identified 8 pieces that were known to all and 8 pieces by the same composers that were known to none. After the scanning sessions, we asked our experimental participants to indicate which of the selections were familiar and which were unfamiliar. In two cases, participants identified an "unfamiliar" piece as familiar, so for the analysis of their data we eliminated both that piece and its matched "familiar" piece.

Familiar	Unfamiliar
J. S. Bach, *Jesu, Joy of Man's Desiring*	J. S. Bach, *Coriolan*
Beethoven, *Fifth Symphony*	Beethoven, *First Symphony*
Beethoven, *Für Elise*	Beethoven, *Moonlight Sonata, 2nd Movement*
Elgar, *Pomp and Circumstance*	Elgar, *Symphony No. 1*
Mozart, *Eine Kleine Nachtmusik, KV 525*	Mozart, *Ein Musikalisher Spab, KV 522*
Rossini, *William Tell Overture*	Rossini, *La Donna*
Strauss, *Blue Danube*	Strauss, *Wine, Women, and Song*
Tchaikovsky, *March from the Nutcracker Suite*	Tchaikovsky, *First Symphony*

Samples of the soundfiles used in the experiment can be heard at http://www.psych .mcgill.ca/labs/levitin/research/musicsamples.html.