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THEORETICAL REVIEW

Processing structure in language and music: a case for shared reliance on cognitive control

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Abstract The relationship between structural processing in music and language has received increasing interest in the past several years, spurred by the influential *Shared Syntactic Integration Resource Hypothesis* (SSIRH; Patel, *Nature Neuroscience,* 6, 674–681, 2003). According to this resource-sharing framework, music and language rely on separable syntactic representations but recruit shared cognitive resources to integrate these representations into evolving structures. The SSIRH is supported by findings of interactions between structural manipulations in music and language. However, other recent evidence suggests that such interactions also can arise with nonstructural manipulations, and some recent neuroimaging studies report largely nonoverlapping neural regions involved in processing musical and linguistic structure. These conflicting results raise the question of exactly what shared (and distinct) resources underlie musical and linguistic structural processing. This paper suggests that one shared resource is prefrontal cortical mechanisms of *cognitive control*, which are recruited to detect and resolve conflict that occurs when expectations are violated and interpretations must be revised. By this account, musical processing involves not just the incremental processing and integration of musical elements as they occur, but also the incremental generation of musical predictions and expectations, which must sometimes be overridden and revised in light of evolving musical input.

Keywords Language · Music · Syntax · Cognitive control · Musical ambiguity

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The impressive human ability to process complex structure is perhaps most evident in language and music. The existence (or nonexistence) of a relationship between musical and linguistic structure (syntax) has received increasing interest over the past several years (for reviews, see Patel, 2008; Slevc, 2012; Tillmann, 2012), partially because this issue speaks to the broad question of modularity: do the complex cognitive systems supporting music and language rely on separable, modular processes (Peretz & Coltheart, 2003), or does syntactic processing in music and language rely, at least in part, on a common system (Patel, 2003)?

The second possibility gains some indirect support from a number of parallels between linguistic and musical structure. Both music and language can be characterized as hierarchical rule-based systems, and similar theories can be used to describe structural organization in both domains. In an influential set of talks, Leonard Bernstein (1976) linked musical structure to generative linguistic theory, leading to the development of several explicit theories of musical structure that draw on linguistic formalisms. The most well-known theory of this type is Lerdahl and Jackendoff's (1983) *generative theory of tonal music* (see also Hamanaka, Hirata, & Tojo, 2006; Lerdahl, 2001), but other linguistically motivated analyses of musical structure have been proposed by Longuet-Higgins (1976), Katz and Pesetsky (2011), and Rohrmeier (2011). Generally speaking, these proposals link hierarchical organization of (Western tonal) music (motivated to some extent by Schenkerian analysis; Schenker, 1935/1979) to a linguistically inspired structure of rules and constraints, leading to a generative theory of harmonic structure. Of course, describing linguistic and musical structure with similar formalisms does not mean the processes themselves are related (Jackendoff, 2009; London, 2012b). Nevertheless, these formal similarities have inspired questions about relatedness between the *processing* of linguistic and musical structure.

Indeed, linguistic and musical structure are not only formally related, but also show developmental, neural, and behavioral similarities. Children implicitly learn the structure of their native language (e.g., Gómez & Gerken, 1999; Saffran, Aslin, & Newport, 2001) and their native musical system (e.g., Corrigall & Trainor, 2010; Hannon & Trainor, 2007) along similar developmental trajectories (Brandt, Gebrian, & Slevc, 2012; McMullen & Saffran, 2004). Developmental deficits in linguistic syntax associated with specific language impairment also can affect structural processing in music (Jentschke, Koelsch, Sallat, & Friederici, 2008), supporting shared processing mechanisms. Both musical and linguistic structure are processed rapidly, and unexpected structural elements in music and in language are associated with similar electrophysiological responses (Koelsch, Gunter, Wittfoth, & Sammler, 2005b; Patel, Gibson, Ratner, Besson, & Holcomb, 1998; Sammler, Koelsch, & Friederici, 2011). In addition, manipulations of harmonic structure in fMRI paradigms show effects in brain areas typically associated with linguistic syntax including (most relevant to the following discussion) left inferior frontal regions, i.e., Broca's area (Janata, Tillmann, & Bharucha, 2002; Koelsch et al., 2002; Koelsch, Fritz, Schulze, Alsop, & Schlaug, 2005a; Minati et al., 2008; Oechslin, Van De Ville, Lazeyras, Hauert, & James, 2013; Tillmann, Janata, & Bharucha, 2003; Tillmann et al., 2006; Seger et al., 2013). These inferior frontal regions have also been implicated in the processing of rhythmic structure (Vuust, Roepstorff, Wallentin, Mouridsen, & Østergaard, 2006; Vuust, Wallentin, Mouridsen, Østergaard, & Roepstorff, 2011), and both frontal and temporal regions show equal sensitivity to temporal structure in music and speech (Abrams et al., 2011). Finally, there is a growing body of behavioral evidence linking the processing of musical and linguistic structure (e.g., Hoch, Poulin-Charronnat, & Tillmann, 2011; Fedorenko, Patel, Casasanto, Winawer, & Gibson, 2009; Slevc, Rosenberg, & Patel, 2009), as discussed below.

Despite substantial evidence for similarities, it also is clear that musical and linguistic structure differ in many ways. For one, they serve quite different purposes. Linguistic structure represents propositional relationships between elements—i.e., who did what to whom. In contrast, musical structure does not reflect relational meaning but rather the relative stabilities of pitches in a tonal context and aesthetic/emotional patterns of tension and relaxation (for discussion, Jackendoff, 2009; London, 2012b). Empirically, distinct patterns of activation in recent functional neuroimaging studies of language and music (e.g., Rogalsky, Rong, Saberi, & Hickok, 2011) and double dissociations between musical and linguistic processing deficits (i.e., *amusia* and *aphasia*; see Peretz, 2006, for a review) suggest distinct neural systems underlying music and language. Although this work has not generally investigated structural processing per se, it does seem that deficits in musical structural processing can accompany preserved syntactic processing in language (Peretz, 1993) and that deficits in linguistic syntactic processing can accompany preserved processing of musical structure (Basso & Capitani, 1985).[1] Reconciling these differences with evidence for shared structural processing requires a more nuanced view of musical and linguistic structure that includes both shared and distinct elements of structure across domains.

Music/language interactions and the shared syntactic integration resource hypothesis

An influential reconciliation of this type is Patel's (2003; 2008; 2012) *shared syntactic integration resource hypothesis* (SSIRH), which claims that music and language rely on separable representations (e.g., nouns and verbs in language, tonal functions in music) but recruit a shared set of syntactic processing resources to integrate these separate representations into evolving sequences. The SSIRH is an appealing hypothesis because it can account both for similarities in the processing of musical and linguistic structure while also accounting for neuropsychological dissociations between processing of music and language.

There is a growing body of evidence supporting the SSIRH, much of it relying on interference paradigms where participants are simultaneously presented with both musical and linguistic stimuli. In these paradigms, syntactic manipulations in both domains are crossed to look for interactive effects that indicate shared processing (in contrast to additive effects, which would indicate independent processes; Sternberg, 1969). For example, an electrophysiological effect characteristic of linguistic syntactic violations (the left anterior negativity, or LAN) is reduced when the linguistic manipulation is paired with a concurrent music-syntactic irregularity (Koelsch et al., 2005b). Similarly, facilitation for syntactically expected words in a lexical decision task is reduced when paired with harmonically unexpected chords (Hoch et al., 2011), and comprehension of sung complex sentences (object relative clauses) is worse when the critical regions are sung out-of-key (Fedorenko et al., 2009; cf. Fiveash & Pammer, 2014).

Slevc et al. (2009) relied on temporary syntactic ambiguities (*garden path* sentences), where readers are slower to comprehend the disambiguating word *was* in a sentence, such

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[1] It is worth noting that, while Basso and Capitani's (1985) patient NS did show preserved harmonic processing despite quite severe global aphasia, it is not actually clear whether his ability to process linguistic structure was deficient because his severe anomia and apraxia make it difficult to evaluate his syntactic processing abilities per se. In fact, we know of no unambiguous reports of agrammatic individuals who show preserved harmonic processing in music. In addition, there is at least some evidence that agrammatism is associated with harmonic processing deficits in online tasks (Patel et al., 2008).

as “The scientist proved the hypothesis was false” compared to an unambiguous context, such as “The scientist proved *that* the hypothesis was false.” This slowed processing presumably reflects the need to revise an initial syntactic interpretation where “the hypothesis” was interpreted as the direct object of the verb proved rather than as the subject of an embedded sentence complement (Pickering & van Gompel, 2006, for review). This garden path effect was more pronounced when the disambiguating word (*was*) was accompanied by a harmonically unexpected chord (but not when accompanied by a chord of unexpected timbre). Importantly, there was no such interaction between harmonic unexpectancy and *semantic* unexpectancy in language. That is, while reading was slowed for semantically unexpected words, such as *pigs*, in the sentence, “The boss warned the mailman to watch for angry *pigs* when delivering the mail” (compared to the expected *dogs*), this effect did not differ as a function of the harmonic expectancy of the chord accompanying the critical (semantically surprising) word. This suggests that the interactive effects between musical structure and language are specific to syntax.

However, a more recent finding casts doubt on this last conclusion: the same harmonic manipulations used by Slevc et al. (2009) did lead to interactive effects when paired with sentences containing “semantic garden paths” (Perruchet & Poulin-Charronnat, 2013). These were sentences, such as “When the exterminator found the bug, he quickly unplugged the spy equipment from the wall,” where the reader presumably interprets the semantically ambiguous word *bug* as referring to an insect until encountering the disambiguating information *unplugged the spy equipment*. This type of sentence is analogous to a syntactic garden path in the sense that a previous interpretation must be revised (as *bug* actually turns out to be referring to eavesdropping equipment); however, it differs in that this revision is—critically—not structural in nature. This interaction between a harmonic manipulation and a nonstructural manipulation in language suggests that shared integration resources between music and language are not limited to syntax per se (see also Poulin-Charronnat, Bigand, Madurell, & Peereman, 2005; Steinbeis & Koelsch, 2008).

One might then imagine that what drives interactions between musical and linguistic structural processing is simply sensory attention (Poulin-Charronnat et al., 2005). This account is supported by demonstrations that the effects of many types of harmonic structural manipulations can be explained in terms of plausible sensory mechanisms (Collins, Tillmann, Barrett, Delbé, & Janata, 2014) and that harmonic manipulations can influence the attention devoted to concurrent nonmusical (and non-linguistic) tasks (e.g., Escoffier & Tillmann, 2008). However, it seems unlikely that the interactions between harmonic and linguistic structure described above are due entirely to shared reliance on attentional resources for two reasons. First, nonstructural musical manipulations of timbre or amplitude—investigated as controls for attentional capture—do not interact with linguistic syntactic or semantic manipulations (Fedorenko et al., 2009; Fiveash & Pammer, 2014; Koelsch et al., 2005b; Slevc et al., 2009). Second, although semantically surprising words presumably also capture attention, manipulations of harmonic structure have generally not been found to interact with semantic unexpectancy (Besson, Faïta, Peretz, Bonnel, & Requin, 1998; Bonnel, Faïta, Peretz, & Besson, 2001; Hoch et al., 2011; Koelsch et al., 2005b; Perruchet & Poulin-Charronnat, 2013; Slevc et al., 2009; but see Poulin-Charronnat et al., 2005; Steinbeis & Koelsch, 2008). Thus, neither processes specific to syntactic processing nor general attentional mechanisms seem to adequately predict when musical and linguistic parsing do and do not interact.

Neuroimaging evidence is similarly mixed. Although musical manipulations do activate “language regions” in frontal cortex (e.g., Koelsch et al., 2005b; Minati et al., 2008; Seger et al., 2013; Tillmann et al., 2006; Vuust et al., 2011), these fMRI studies have not examined musical and linguistic manipulations in the same participants, and thus do not necessarily show that the *same* neural regions are involved in the processing of musical and linguistic structure (cf. Fedorenko & Kanwisher, 2009). In fact, most of the few recent studies that have included within-subjects comparisons of linguistic and musical manipulations have not found substantial overlap between neural regions implicated in the processing of language and music (but see Abrams et al., 2011). For example, Fedorenko and colleagues (Fedorenko, Behr, & Kanwisher, 2011; Fedorenko, McDermott, Norman-Haignere, & Kanwisher, 2012) used a contrast between intact sentences and lists of unconnected words (visually presented word-by-word) to define a series of language-sensitive brain regions of interest (ROIs) for each participant, and then investigated whether a musical manipulation significantly engaged those same regions. The musical manipulation—a contrast between 24 second clips of rock/pop songs and pitch- and rhythm-scrambled versions of those same clips—did not lead to significant effects in the language-ROIs (frontal or otherwise), suggesting largely separable neural processes for language and music. But even these within-participant findings are equivocal; while comparing intact sentences versus nonword lists does broadly capture linguistic syntactic and semantic processing, it is less obvious that listening to pitch- and rhythm-scrambled music results in the *absence* of musical processing. In addition, these cross-modality comparisons—reading words vs. listening to music—may lead to increased separation. In a related paradigm, Rogalsky et al. (2011) found that listening to novel melodies (compared to silence) showed little or no overlap with a contrast between listening to intact “jabberwocky” sentences and scrambled sentences. However, neither the musical nor linguistic contrasts revealed prefrontal activation typically associated with syntactic processing (see

Friederici, 2011, for a review). Nevertheless, the point remains that there is little direct evidence for colocalization of structural processing in music and language.

In sum, there is a growing body of evidence for shared processing of music and language, but also a growing body of work suggesting nonoverlapping processes. This motivates a reassessment of exactly what resources might be shared (and distinct) across domains.

Cognitive control as a shared resource

Resources that are shared between music and language must be those that link musical structural processing to some aspects of linguistic processing but *not* to other aspects. Specifically, musical structure processing seems to share resources involved in processing syntactic errors (Hoch et al., 2011; Koelsch et al., 2005b; Steinbeis & Koelsch, 2008), syntactic complexity (Fedorenko et al., 2009; Fiveash & Pammer, 2014), and both syntactic and semantic garden paths (Perruchet & Poulin-Charronnat, 2013; Slevc et al., 2009), but not resources involved in processing semantically surprising words (Hoch et al., 2011; Koelsch et al., 2005b; Perruchet & Poulin-Charronnat, 2013; Slevc et al., 2009)[2] or related to the difference between intact and scrambled sentences (e.g., Fedorenko et al., 2012). One way to characterize this distinction is that the aspects of language processing that do interact with musical structure require not only the processing of an unexpected element, but also the revision or reinterpretation of a previous commitment to a particular (syntactic or semantic) interpretation. Aspects of language processing that do not interact with musical manipulations, in contrast, may be those that do not require *reinterpretation* per se; for example, there is no obvious need to revise a previous interpretation when encountering a semantically surprising word or any clear way to revise the structural or semantic interpretation of a scrambled sentence.

Revision or reinterpretation in these cases likely relies on the detection of conflict between new information and a current incrementally constructed interpretation, and also on the resolution of this conflict by biasing activation away from a current interpretation and toward a new one. This sort of conflict detection and resolution draws on processes of *cognitive control* that allow for the regulation of mental activity and the ability to adjust (on-the-fly) in the face of conflicting information (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Miller & Cohen, 2001). This regulation of internal representations is distinct from mechanisms of perceptual (or "external") attention (Elton & Gao, 2014; Chun, Golomb, & Turk-Browne, 2011; Lavie, Hirst, de Fockert, & Viding, 2004; Seeley et al., 2007) and is part of the flexible, goal-directed abilities associated with the prefrontal cortex (Miller & Cohen, 2001). There are two main components of cognitive control that are associated with distinct neural regions. Monitoring for and detecting conflict is primarily associated with the dorsal anterior cingulate cortex (dACC) (Botvinick et al., 2001; Shenhav, Botvinick, & Cohen, 2013; Yeung, Botvinick, & Cohen, 2004). Conflict detection then leads to regulatory activity in the lateral prefrontal cortex (e.g., Kerns, Cohen, MacDonald, Cho, Stenger, & Carter, 2004; Kouneiher, Charron, & Koechlin, 2009), with increasingly more abstract forms of control recruiting increasingly more anterior/rostral regions (following a more general "gradient of abstractness" in the prefrontal cortex; Badre & D'Esposito, 2009; Koechlin & Summerfield, 2011). The resolution of relatively abstract representational conflict (versus response conflict) is assumed to rely importantly on the left inferior frontal gyrus (LIFG) including Broca's area (e.g., Badre & Wagner, 2007; Miller & Cohen, 2001; Novick, Trueswell, & Thompson-Schill, 2005; 2010). Given that Broca's area—a classical language region—is involved in cognitive control, it is perhaps unsurprising that the role of cognitive control in linguistic syntactic processing is part of a larger debate on the role of Broca's area in language (see Rogalsky & Hickok, 2011, for discussion).

While cognitive control is typically investigated using nonlinguistic tasks, such as the Stroop task (MacLeod, 1991; Stroop, 1935), or memory tasks that manipulate proactive interference (Jonides, Smith, Marshuetz, Koeppe, & Reuter-Lorenz, 1998), aspects of linguistic parsing have been argued to critically rely on cognitive control to detect and resolve conflict that occurs when expectations are violated and interpretations must be revised (Novick et al., 2005; 2010). Conflict resolution in language can be syntactic in nature; for example, LIFG-based cognitive control processes have been implicated in resolution of syntactic conflict in garden path sentences (January, Trueswell, & Thompson-Schill, 2009; Novick, Kan, Trueswell, & Thompson-Schill, 2009). Importantly, cognitive control also is recruited to resolve nonsyntactic conflicts; for example the LIFG is recruited when resolving conflict between semantic plausibility and thematic roles (Thothathiri, Kim, Trueswell, & Thompson-Schill, 2012; Ye & Zhou, 2008; 2009), resolving competition in lexical selection (Schnur et al., 2009), and resolving semantic ambiguities (Bedny, Hulbert, & Thompson-Schill, 2007; Rodd, Johnsrude, & Davis, 2010; Vuong & Martin, 2011).

These findings map relatively straightforwardly onto the cases where linguistic manipulations interact with musical structure. In particular, garden path sentences (Slevc et al., 2009) and morpho-syntactic errors (Hoch et al., 2011; Koelsch et al., 2005b) involve reinterpretation of an incrementally constructed initial syntactic analysis based on late-arriving syntactic information (cf. Novick et al., 2005).

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[2] See the Conclusions section below for discussion of some exceptions to this generalization.

Syntactic complexity effects (Fedorenko et al., 2009; Fiveash & Pammer, 2014) involve resolving temporary structural ambiguities and overcoming interference when establishing complex or long-distance dependencies (Fernandez-Duque, 2009; Lewis, Vasishth, & Van Dyke, 2006), and semantic garden paths (Perruchet & Poulin-Charronnat, 2013) involve reinterpretations based on incompatible semantic interpretations of homophones (Rodd et al., 2010). Thus, studies finding interactive effects between musical structure and language (be it linguistic syntax or non-syntactic situations that require resolution between conflicting representations like semantic garden paths) may be revealing simultaneous use of cognitive control resources. Because cognitive control is important primarily when there is a need to regulate mental activity, these relationships may be most evident when listeners are *actively* processing music and language. Indeed, one general distinction between studies of musical (and linguistic) processing that do and do not implicate prefrontal cortical regions associated with cognitive control is that frontal activation is found in studies employing active tasks (e.g., categorization or tapping tasks), whereas studies finding no frontal involvement typically employ passive listening (but see Abrams et al., 2011; Levitin & Menon, 2003). This suggests that active processing may be a prerequisite for the involvement of control processes (cf. effects of active processing tasks in other domains, such as vision (Beauchamp, Haxby, Jennings, & DeYoe, 1999). If music/language interactions do reflect shared reliance on cognitive control, active musical syntactic processing as measured in the studies cited above also must rely on cognitive control mechanisms.

Ambiguity and cognitive control in musical structure

The claim that cognitive control is, in fact, a shared mechanism implies that aspects of music perception rely on cognitive control. Indeed, this is likely to be the case. Listening to music involves building up complex cognitive representations of musical structure over time. This involves not only the incremental processing and integration of musical elements as they occur, but also the incremental generation of musical predictions and expectations (for a recent discussion, see Rohrmeier & Koelsch, 2012). One hazard of this predictive processing is that new information can be inconsistent with one's prediction, thus harmonic processing requires both the ability to detect conflict between predicted and observed percepts and the ability to resolve this conflict by overriding and updating an evolving representation of musical structure.

Conflict between musical percepts and predictions likely arises in many situations, not the least of which is cases of musical ambiguity (Bernstein, 1976; Jackendoff, 1991; Temperley, 2001; Thompson, 1983; see also Lewin, 1986). Structural ambiguity in music is common and occurs across diverse musical genres—not only in classical works (e.g., Smith, 2006; Temperley, 2001; Thompson, 1983), but also in jazz and blues (e.g., Blake, 1982; Ripani, 2006), rock music (e.g., McDonald, 2000; Hesselink, 2013), and electronic dance music (e.g., Butler, 2001; 2006). Of course, structural ambiguity is not limited to the Western musical tradition (e.g., Scherzinger, 2010; Stevens, 2012), but here we perpetuate a weakness of many cognitively oriented studies on musical structure by focusing on Western tonal music.

Jackendoff (1991) distinguishes between two general accounts of how a listener could parse a musically ambiguous structure. One possibility is that parsing is serial: listeners commit to a single analysis at any point in time, choosing the most probable analysis in the face of ambiguity. When confronted with newly arriving information that is inconsistent with this parse, listeners would experience a "musical garden path" and have to revise their previous structural parse (alternatively, revision might not occur immediately, but only after sufficient evidence has accumulated). This serial parsing model is essentially analogous to the two-stage "garden path model" of sentence parsing (Frazier, 1987; Ferreira & Clifton, 1986), where the parser first forms a syntactic analysis based only on bottom-up information, then revises based on other available information (if necessary) in a second stage. Alternatively, musical parsing might be parallel, where multiple structural hypotheses are entertained at any given point, with more likely analyses (i.e., those that are better supported by any available data) given more weight. This is analogous to interactive constraint-based (or constraint-satisfaction) models of sentence parsing (e.g., MacDonald, Pearlmutter, & Seidenberg, 1994; McClelland, St. John, & Taraban, 1989) where all possible sentence analyses are activated in parallel, to the extent that they are supported by all available sources of information.[3] Of course, a third possibility is that listeners do not resolve musical ambiguity at all and simply do not assume structural coherence (cf. Cook, 1987; Tillmann, Bigand, & Madurell, 1998).

Under either serial or parallel accounts of ambiguity resolution, when a musical piece provides new information that is inconsistent with a first or a dominant analysis, that primary analysis may need to be revised (or activation of alternative analyses adjusted) to incorporate this new information. The detection of conflict between these structural analyses and the revision of a previously formed musical interpretation in light of newly arriving information are exactly the sort of processes served by cognitive control. There are many types of musical

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[3] It seems unlikely that multiple musical (or linguistic) analyses are *consciously* available simultaneously; instead, musically ambiguous stimuli might be better construed as cases of multistability, such as the Necker cube, where only one interpretation can be experienced at a time (Repp, 2007). However, it remains possible that mechanisms of musical parsing construct and consider multiple analyses at some unconscious level of representation.

ambiguity that might draw on cognitive control mechanisms; we focus on ambiguity in meter, harmony, tonality, and contrapuntal structure (Temperley, 2001).

Perhaps the most easily apparent form of musical ambiguity is metrical, when the apparent meter of a piece of music changes and must be reevaluated. Meter refers to the perceived organization of a series of beats, including both their cyclic pattern and additional higher levels of temporal structure. It is distinct from rhythmic grouping in that it relies on our endogenous perception of musical rhythm (as can be seen, for example, by our ability to synchronize to syncopated rhythms where the acoustic signal may not correspond to the beat). Meter perception may be driven by entrainment (Repp, 2007) and temporal expectancies (Large & Palmer, 2002; London, 2012a). Because of the predictive and entraining nature of metrical perception, listeners not only interpret incoming music in terms of a metrical structure, but form expectations and predictions about future metrical events.

A melodic line is metrically ambiguous when it can be perceived in one of several possible meters (Fig. 1). In such cases, an ambiguous stimulus is presumably interpreted with the most plausible meter until later information conflicts with that first metrical interpretation (Jackendoff, 1991; Temperley, 2001). In order to form a coherent structure of the piece overall, the listener must resolve the conflict between the new musical information and the currently entrained/predicted pattern; this detection and reconstruing of meter forms a type of "rhythmic garden path," as illustrated in Fig. 2.[4] To our knowledge, there has been only one attempt to investigate whether listeners actually *resolve* a disambiguated metrical interpretation: Vazan and Schober (2004) asked listeners to tap along to a song where an ambiguous rhythm is strongly biased toward a triple meter but later resolves to a duple meter ("Murder by Numbers" by The Police). Over multiple rehearings, only a few participants showed evidence of having reinterpreted the initial rhythmic structure (by tapping in duple meter from the beginning), suggesting that many listeners do not successfully revise metrical ambiguities, at least in this particular song (Vazan & Schober, 2004). Note, however, that metrical ambiguity is not always disambiguated or resolved; some types of music may actively engage listeners precisely because of long-lasting ambiguity in meter (e.g., Butler, 2006). Managing these multiple interpretations also is likely to draw on cognitive control mechanisms. Consistent with this claim, keeping a specific rhythm in a polyrhythmic context engages the LIFG, an area often associated with cognitive control (Vuust et al., 2006; 2011). In fact, Vuust and colleagues speculate that "the inferior frontal lobe is crucially involved in processing discrepancy or tension between the anticipatory neuronal model and relevant features of the incoming stimuli, be it in language, music or other communicational systems." (Vuust et al., 2011, p. 216).

Musical ambiguity can occur in harmonic structure as well (cf. Lewin, 1986). Figure 3 shows an example of a chord that, heard in isolation, can be perceived as either a C Major chord or an A minor chord, because it only contains two pitches: C and E. The notes C-E-G would make a C Major chord and the notes A-C-E would make an A minor chord. However, these types of chords are rarely perceived as ambiguous, because they are usually interpreted within their surrounding harmonic context. In Fig. 3, the interpretation of this two-note chord is colored by the context. In the context of 3a, the chord is perceived as C Major, but the same chord, in the context of 3b, is perceived as A minor.

A closely related form of ambiguity is tonal ambiguity. In contrast to harmonic ambiguity, which refers to individual ambiguous chords (Fig. 3), tonal ambiguity deals with a piece's overall key. Just as listeners build up expectations of metrical structure, they also predict information about the tonal structure of an evolving musical piece. Changes in musical structure often occur with diatonic *pivot chords*, which are common to at least two different keys (and are thus harmonically ambiguous—when heard in isolation, they alone do not establish a key). Pivot chords can serve as a smooth transition between two keys, because they are harmonically appropriate in either key. For example, the circled chord in Fig. 4 acts as a minor six chord (vi^6) in the key of C Major, but also as a minor two chord (ii^6) in the new key of G Major.

In the case of a pivot chord modulation (and most other types of modulation), the pivot chord (e.g., the A minor chord in Fig. 4) is initially interpreted as belonging to the original key. However, the following chords are unambiguously in another key, which may lead listeners to reinterpret the pivot chord and to revise their analysis of the musical key as the music continues. If listeners do, in fact, reinterpret both the pivot chord itself and the tonal center of the piece from the pivot chord onward, this can be characterized as a "tonal garden path," which likely relies on the information recharacterization processes of cognitive control. This sort of tonal garden path is likely not limited to diatonic pivot chords, but may instead result from any sort of harmonic change that requires reevaluation of a previous tonal analysis. The harmonic manipulations that lead to music/language interactions are of this sort: both relatively coarse manipulations of musical key (e.g., Koelsch et al., 2005b; Slevc et al., 2009) and more subtle manipulations of tonal function (e.g., Hoch et al., 2011) likely involve reinterpretation of a previously established harmonic context, and thus draw on cognitive control. Of course, many of the manipulations used in investigations of music/language interactions are not resolvable ambiguities and it is not obvious that a harmonic context can be reinterpreted based on a single chord from another key.

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[4] For additional examples and a taxonomy of different types of metrical ambiguity, see Justin London's collected list of "metric fakeouts," available from http://people.carleton.edu/~jlondon/.

Fig. 1 (**a**) A melodic line that can be perceived with different metrical analyses. (**b**) Analysis of the melody in 4/4 time, with the strongest pulses on the first and third beats (the number of dots indicate the perceived strength of the pulses). (**c**) Analysis of the melody in 3/4 time with the strongest pulses on the downbeats of every measure. (**d**) Alternative analysis in 4/4 time with the first C treated as a pick up note instead of the downbeat

However, such an unexpected tonal event likely still elicits an attempt at reconciliation, even if it is eventually abandoned. This attempt may occur as an automatic consequence of ACC-mediated conflict detection that occurs when new information conflicts with an expected tonal event (e.g., a tonic at the end of a cadence) or set of expected possibilities (e.g., possible chords from a particular key), which automatically signals prefrontal conflict resolution mechanisms. Alternatively, reinterpretation may not be so automatic, in which case one might observe reduced harmonic unexpectancy effects over the course of an experiment as participants realize that out-of-key and unresolvable chords are relatively common (although this has not been directly investigated as far as we know, it seems plausible given, e.g., evidence that participants rapidly develop expectancies based on a new musical system; Loui, Wu, Wessel, & Knight, 2009).

Another type of musical ambiguity concerns the number of voices in a melodic line. This is referred to as contrapuntal ambiguity (Temperley, 2001) and draws on theories of auditory scene analysis (Bregman, 1990; see Moore & Gockel, 2012, for a review). When listening to music, we hear it as coming from one or more sources, or *streams*. *Fission* (stream segregation) describes perception of a sequence of sounds as two or more separate streams. Conversely, *fusion* describes perception of a sequence of sounds as a single stream. Differences in pitch, loudness, timing, and timbre all affect how one perceives auditory streams (e.g., Iverson, 1995; Micheyl, Hanson, Demany, Shamma, & Oxenham, 2013); for instance, listeners may perceptually group notes that are most proximal in pitch, thus more distant pitches tend to be heard as two segregated streams. An example of this is shown in Fig. 5a, where the music comes from a single source, but the differences in pitch induce the listener to segregate the sequence into two streams (for related examples, see Deutsch, 1987; 1999; Dowling, Lung, & Herrbold, 1987).

This type of contrapuntal ambiguity can occur in fugues, which contain multiple voices. For instance, the subject in the first three measures of Fig. 5b could initially be perceived as two voices (notated in dark blue and light blue) until the arrival of the answer (in red) in measure four. At this point, the listener may revise this segregated perception of the first voice (the subject) into a single fused interpretation, with the new information in the answer now interpreted as a second voice. This revision of melodic voices into fused or segregated

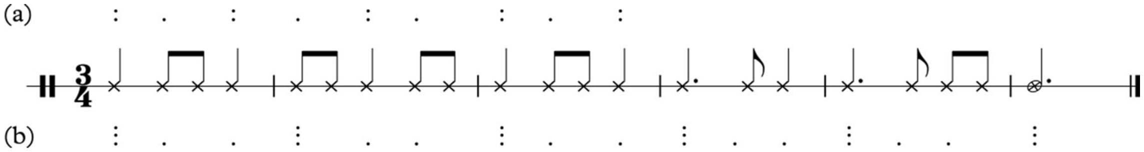

Fig. 2 A "rhythmic garden path" in which the listener may initially perceive the ambiguous meter as 2/4 time (metric analysis **a**) or in 3/4 time (metric analysis **b**). However, upon reaching measure 4, in which the rhythm is most common to 3/4 time, one would need to reconcile the predicted metric interpretation to 3/4 time and potentially revise the interpretation of the preceding rhythm

Fig. 3 The two-note chord in the first measure is harmonically ambiguous, because it contains only the notes C and E. (**a**) A context typical of the key of C Major, where the ambiguous chord is thus perceived as C Major. (**b**) A context typical of the key of A minor, where the ambiguous chord is thus perceived as A Minor

sources is yet another instance that likely relies on the information recharacterization functions of cognitive control.

Evidence for a cognitive control/music link

These situations of musical ambiguity and revision suggest an important role for cognitive control in musical processing; however, there is, as of yet, very little work that directly investigates if and how music perception relies on cognitive control. Some indirect evidence comes from findings that musical training is associated with advantages in cognitive control ability (Bialystok & DePape, 2009; Pallesen et al., 2010; Moreno et al., 2011; Travis, Harung, & Lagrosen, 2011; but see Schellenberg, 2011), among other types of cognitive advantages (Schellenberg & Weiss, 2012). Transfer from musical training to cognitive control is predicted only if the demands of musical processing tax (and thus potentially strengthen) cognitive control processes (cf. Hussey & Novick, 2012). If so, this “musician advantage” in cognitive control may occur because extensive training and experience with the aspects of music discussed above place additional demands on cognitive control mechanisms, thus serving as a sort of naturalistic cognitive control training (cf. discussions of enhanced cognitive control associated with bilingualism; e.g., Bialystok, Craik, Green, & Gollan, 2009).[5]

Consistent with this link, musicians have greater grey matter density than nonmusician controls in LIFG (Abdul-Kareem, Stancak, Parkes, & Sluming, 2011; Gaser & Schlaug, 2003; Sluming et al., 2002), an area associated with cognitive control (Badre & Wagner, 2007; Botvinick et al., 2001; Miller & Cohen, 2001). Functional neuroimaging studies that manipulate musical structure—typically in terms of tonal (Koelsch et al., 2002; Koelsch et al., 2005a; Oechslin et al., 2013; Tillmann et al., 2003; 2006; Seger et al., 2013) or rhythmic ambiguity (Vuust et al., 2006; Vuust et al., 2011) find activation in left and right lateral prefrontal areas also associated with cognitive control. This apparent overlap is illustrated in Fig. 6, which shows peak activations from these studies along with regions that are consistently reported in studies of a prototypical cognitive control task (the Stroop task, based on an automated meta-analysis from the Neurosynth database; Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011). Although overlap should be interpreted with caution because these data come from different studies, it does appear that frontal peak activations cluster within or near areas associated with cognitive control in both hemispheres. Given evidence for a posterior-anterior gradient of abstractness in the prefrontal cortex (see above), it is somewhat surprising that the frontal activation peaks from these few studies of musical ambiguity do not appear to be clustered in anterior regions but are spread relatively evenly across inferior frontal regions bilaterally. (In contrast, note that language processing does seem to show a posterior-anterior gradient of abstractness: phonological processing engages more posterior regions of the LIFG, namely BA 44/45, whereas semantic and syntactic processing engage more anterior regions, namely BA 45/47; e.g., Hagoort, 2005; 2013; Poldrack, Wagner, Prull, Desmond, Glover, & Gabrieli, 1999).

This apparent overlap for frontal regions involved in active (task-relevant) processing of musical structure and in resolving Stroop interference is suggestive of a neural relationship between musical structure and cognitive control; however, it remains only suggestive without studies investigating these processes in the same participants (cf. January et al., 2009; Ye & Zhou, 2009). In fact, some recent work has not found significant overlap between musical and linguistic manipulations within participants (Fedorenko et al., 2011; 2012; Rogalsky et al., 2011), perhaps because these studies used passive listening instead of tasks and manipulations that would be expected to recruit cognitive control. Thus, an

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[5] It is important to note that these cognitive control advantages (and the neuroanatomical differences discussed below) have largely been reported in correlational studies; thus, it is possible that they reflect—at least in part—preexisting differences between people who do and do not decide to pursue musical training (e.g., Corrigall et al., 2013; but see Norton et al., 2005).

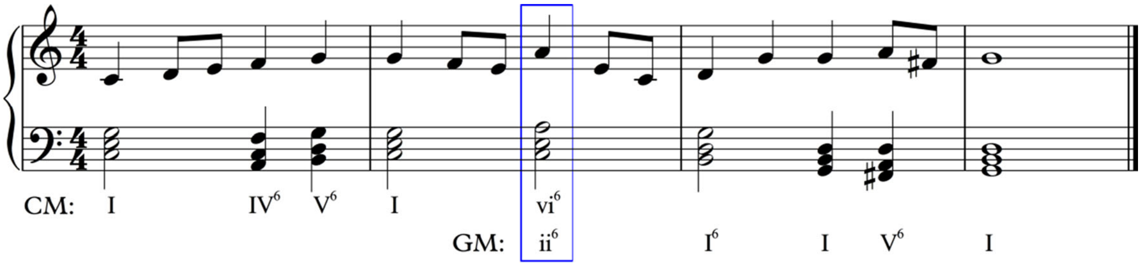

Fig. 4 A chorale beginning in the key of C Major, which then modulates into G Major. The transition occurs via the circled A minor pivot chord, which is common to both keys: it is likely initially perceived a vi^6 chord (i.e., is a minor six chord in C Major), but may be reinterpreted as a ii^6 chord (a minor two chord) in G Major, thus acting as a tonal garden path

important future direction will be to investigate potential colocalization using tasks requiring active processing and manipulations likely to lead to conflict resolution in music and language (e.g., comparing garden path sentences with musical garden paths).

More direct evidence for a role of cognitive control in musical processing comes from recent findings of interference between harmonic manipulations and a classic cognitive control task (Masataka & Perlovsky, 2013; Slevc, Reitman, & Okada, 2013). These experiments relied on the Stroop effect (MacLeod, 1991; Stroop, 1935), where participants are slower to name the ink (or font) color of printed stimuli when the word and color are incongruent (e.g., the word "BLUE" printed in green font) than for neutral conditions (e.g., the string "####" printed in green font). This Stroop interference is a prototypical measure of cognitive control, as participants must override a well-learned and automatized response (reading a printed word) to produce a task-relevant (but nonautomatic) response (naming the color of the printed word). Masataka and Perlovsky (2013) found greater Stroop interference when participants heard music containing harmonically unexpected intervals compared to when they heard consonant, harmonically expected, music. Slevc et al. (2013) similarly found that participants showed significantly greater Stroop interference following short musical chorales that ended in an unexpected key compared with chorales that ended on the tonic chord. However, the Stroop effect was not larger when paired with a final chord of surprising timbre, indicating that this interaction did not reflect shared reliance on attention. Instead, these data suggest that unexpected harmonic information taxed cognitive control resources, thereby reducing the resources available to mitigate Stroop interference.

These are (to our knowledge) the only direct findings linking cognitive control and musical processing, and clearly more work is needed. Nevertheless, this, combined with suggestive evidence for LIFG involvement in musical structural processing and advantages in cognitive control associated with musical training, suggests that cognitive control may indeed play an important role in structural processing in music as well as in language. An important future direction will be to investigate the processing of musical structure in populations with limited cognitive control abilities, such as children, who show protracted development of prefrontal cortex (Huttenlocher & Dabholkar, 1997) and correspondingly protracted development of cognitive control (e.g., Bunge et al., 2002), or patients with cognitive control deficits due to constrained LIFG damage (e.g., Hamilton & Martin, 2005). These approaches have already helped elucidate the role of cognitive control in language processing (e.g., Khanna & Boland, 2010; Novick et al., 2009; Thompson-Schill et al., 2002) and are likely to provide an important window onto the cognitive control/music relationship as well.

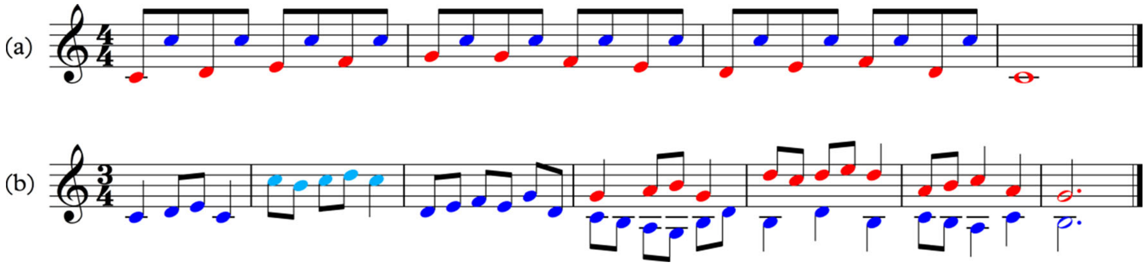

Fig. 5 (**a**) A melodic line that can be perceived with different contrapuntal analyses (i.e., as coming from different numbers of voices). Because of the large differences in pitch, the blue and red notes are likely perceived as two separate streams. (**b**) An example of a fugue with a "contrapuntal garden path." The first three measures (the subject of the fugue) would likely be initially perceived as two voices (notated in dark blue and light blue); however, in measure 4, when the answer (notated in red) begins (and the countersubject, notated in blue, continues) the subject and countersubject may be reinterpreted as representing a single voice

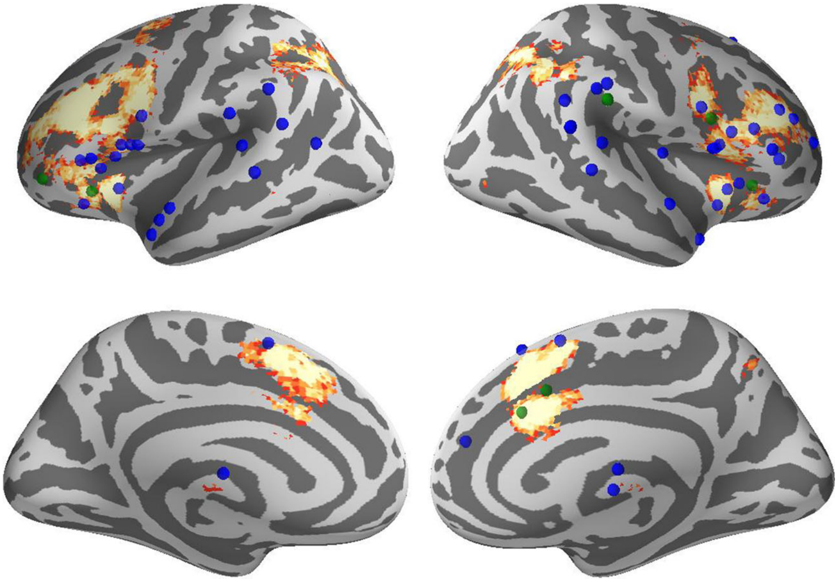

Fig. 6 Regions consistently reported in fMRI studies of the Stroop task—a prototypical measure of cognitive control—and locations of peak activations from fMRI studies of harmonic and rhythmic ambiguity. The activation map of the Stroop task comes from an automated meta-analysis of 101 studies from the Neurosynth database (forward inference map with a threshold of $p < 0.05$ and FDR corrections for multiple comparisons downloaded 6/17/2014 from http://neurosynth.org; Yarkoni et al., 2011). Blue circles indicate peak activations from six fMRI studies of harmonic structure (Koelsch et al., 2002; Koelsch et al., 2005a; Oechslin et al., 2013; Tillmann et al., 2003; 2006; Seger et al., 2013) and green circles indicate peak activations from two fMRI studies of rhythmic ambiguity (Vuust et al., 2006; Vuust et al., 2011)

Conclusions

We take the basic tenet from the SSIRH that structural processing in music and language relies on shared processing resources, but suggest that those shared resources are not limited to syntactic integration, but are rather more basic mechanisms of cognitive control that subserve both domains (cf. Novick et al., 2005; 2010). This proposal is not new, but follows earlier suggestions that music and language interactions reflect shared reliance on domain-general mechanisms (Hoch et al., 2011; Koelsch, 2012; Poulin-Charronnat et al., 2005; Tillmann, 2012; among others). However, this proposal differs from previous work: cognitive control is a different shared mechanism than attentional resources (e.g., Chun et al., 2011; Seeley et al., 2007), and conflict resolution and reinterpretation is a more mechanistic explanation than shared mechanisms of structural and temporal integration. An underlying reliance on cognitive control thus has somewhat more explanatory power: it predicts both when interactions between music and language arise (specifically, when harmonic and linguistic reinterpretation co-occur) and when harmonic and linguistic manipulations produce independent effects (e.g., with manipulations that are surprising but produce relatively little need for conflict resolution and reinterpretation, such as manipulations of musical timbre or amplitude or semantically improbable words).

Note, however, that not all evidence clearly fits this prediction. Although most work has not found interactions between the processing cost of semantically unexpected words (i.e., words with low cloze probability) and structural manipulations in music (Besson et al., 1998; Bonnel et al., 2001; Hoch et al., 2011; Koelsch et al., 2005b; Perruchet & Poulin-Charronnat, 2013; Slevc et al., 2009), there are two studies that have found such interactive effects. Poulin-Charronnat et al. (2005) found harmonic priming effects (i.e., faster responses to an expected tonic chord than a less expected subdominant chord) only when an accompanying sentence ended on an expected (high cloze) word; harmonic priming was absent when the sentence ended in a semantically unexpected way (but see Hoch et al., 2011). Steinbeis and Koelsch (2008) reported a similar pattern: an ERP effect associated with harmonic unexpectancy (the N500) was reduced when paired with a semantically unexpected sentence ending; however, an ERP signature of semantic unexpectancy (the N400) was not affected by a harmonically unexpected chord. These findings suggest an asymmetrical relationship between musical structure and semantic comprehension such that semantically surprising words can draw cognitive or attentional resources away from chord processing, but unexpected chords do not appear to distract from processing of linguistic meaning (at least in the nonmusician participants tested in these paradigms; cf. Loui & Wessel, 2007). This suggests that effects of semantic unexpectancy on harmonic processing may reflect asymmetric attentional demands (cf. Poulin-Charronnat et al., 2005), whereas the effects of harmonic processing on linguistic reinterpretation reflect additional demands on cognitive control as argued above.

A second (nonexclusive) possibility is that there is an important distinction between the types of musical manipulations used in studies where harmonic/semantic interactions have and have not been found. Experiments reporting harmonic/semantic interactions manipulated the expectancy of a chord at the end of a cadence (i.e., tonic vs. non-tonic; Poulin-Charronnat et al., 2005; Steinbeis & Koelsch, 2008), whereas most cases where harmonic/semantic interactions have not been found manipulated the occurrence of an incongruous chord embedded within an otherwise harmonically consistent context. This may indicate an important distinction between the expectation of a cadential figure (i.e., the facilitative effect of a tonic chord after a dominant at the end of the sequence) and the broader expectancy induced by an activated tonal hierarchy (i.e., the processing cost imposed by a mid-sequence chord from an unexpected key). Featherstone, Morrison, Waterman, and MacGregor (2013) make a similar distinction in an attempt to reconcile conflicting electrophysiological patterns associated with harmonic manipulations: they differentiate *resolved* harmonic incongruities, where there is a return to the original key following an incongruous element (as in within-sequence manipulations), from *unresolved* incongruities, where there is no such return (as in final-chord manipulations). Resolved harmonic incongruities are associated with a late positive ERP component characteristic of reanalysis, perhaps reflecting an attempt to integrate the unexpected element into its local context via engagement of cognitive control. Unresolved incongruities, however, are not associated with late positive waves, but instead typically associated with a negative component (i.e., the N500). This suggests that cognitive control mechanisms may be engaged primarily for within-sequence manipulations, and sequence-final manipulations might instead reflect engagement of more general aspects of sensory attention (cf. end-of-sentence wrap-up effects; Just & Carpenter, 1980). Of course, it is also possible that processing a semantically anomalous word does, in fact, draw somewhat on cognitive control to resolve conflict between a predicted and actual word but that this resolution is relatively undemanding and so leads to relatively little cost. If so, semantic unexpectancy might interact only weakly with harmonic manipulations; in support of this final possibility, Hoch et al. (2011) point out that many of the reported null interactions between semantic and harmonic expectancy are, numerically, suggestive of such effects.

There is clearly need for more work to test exactly when and how specific aspects of musical and linguistic processing interact (cf. Koelsch, 2012). Additional research also is needed to determine if (and if so, when) temporary musical ambiguities are indeed reinterpreted (i.e., if listeners do in fact experience “musical garden paths”; Vazan & Schober, 2004). Nevertheless, it is striking that interactive effects have been demonstrated in precisely those situations where conflict resolution and revision likely play an important role. This does not, of course, imply that the *only* resource shared between music and language is cognitive control; both language and music involve processing complex structural relationships that likely place demands on a variety of cognitive abilities. For example, it is clear that perceptual attention plays a role in both domains (e.g., Escoffier & Tillmann, 2008; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). Two other systems that are particularly likely to play a role in both domains are implicit learning and working memory. Implicit learning plays an important role in the acquisition of complex structural knowledge, both in language (e.g., Saffran, Aslin, & Newport, 1996; see Kuhl, 2004, for a review) and in music (e.g., Ettlinger, Margulis, & Wong, 2011; Loui, Wu, Wessel, & Knight, 2009; Loui, Wessel, & Husdon Kam, 2010; Loui, 2012; Rohrmeier & Rebuschat, 2012). Support for shared reliance on implicit learning mechanisms comes from the finding that musical training (which presumably places additional demands on implicit learning mechanisms) leads to better implicit learning of both musical and linguistic structure (Francois & Schön, 2011). Working memory also has been linked to processing of syntax in language (e.g., Just & Carpenter, 1992; Lewis et al., 2006) and in music (Koelsch et al., 2009; Schulze, Zysset, Mueller, Friederici, & Koelsch, 2011; Williamson et al., 2010) and is associated with the inferior frontal regions that are implicated in both domains (Koelsch et al., 2009; Schulze et al., 2011; but see Fedorenko et al., 2011).

The role inferior frontal regions (and especially Broca’s area) play in structural processing is controversial (see Rogalsky & Hickok, 2011, for discussion from the language perspective); LIFG, in particular, has been associated with cognitive control and working memory but also has been claimed to support syntax-specific processes (at least in language; e.g., Grodzinsky & Santi, 2008) and/or more general types of complex hierarchical relationships, such as action sequences (e.g., Farag et al., 2010; Fitch & Martins, 2014; Koechlin & Jubault, 2006) and mathematical structure (Friedrich & Friederici, 2009; Maruyama, Pallier, Jobert, Sigman, & Dehaene, 2012). Thus, these frontal regions that may be associated with shared musical/linguistic processing likely reflect a variety of underlying cognitive processes; a greater understanding of the ways in which linguistic and musical manipulations involve LIFG (and its right-hemisphere homologue) will likely add important data to this debate. A related prediction is that the processing of both music and language should interact with—and show neural overlap with—other domains that rely on cognitive control mechanisms. There is already evidence for some relationships of this type; for example, structural processing in music interacts with arithmetic processing (Hoch & Tillmann, 2012) and with Stroop interference (Masataka & Perlovsky, 2013; Slevc et al., 2013). In addition, “action syntax,” or meaningful structured sequences of actions, may be related to structural processing in both music and language (Harding et al., 2011; Fazio et al., 2009; Fadiga, Craighero, & D'ausilio, 2009; Fitch & Martins, 2014; Jackendoff, 2009; Sammler, Novembre, Koelsch, & Keller, 2013). Of course, cognitive control processes are not restricted to LIFG; it is clear that both left and right frontal mechanisms are involved in cognitive control (e.g., Aron, 2008; Gläscher et al., 2012), including in the sorts of revision-demanding situations discussed here (e.g., there is bilateral IFG involvement in the processing of lexical ambiguity; Klepousniotou, Gracco, & Pike, 2013). Because musical manipulations often involve bilateral frontal activation (see Fig. 6, and Koelsch, 2011, for review), musical processing may be particularly well suited to investigate the role of right frontal regions in complex cognition.

The claim that interactive effects of musical and linguistic structure reflect conflict resolution and revision via a shared reliance on cognitive control mechanisms can be taken in at least two ways. One conclusion might be that linguistic and musical syntax are largely distinct, domain-specific "competence" systems that can place similar "performance" demands on domain-general cognitive processes (cf. Chomsky, 1965). This fits with the idea that language and music are domain-specific modular systems that only interact with general cognitive abilities in limited ways (e.g., Fedorenko et al., 2011; Peretz & Coltheart, 2003). Alternatively, one could conclude that linguistic syntax, musical structure, action sequences, and the like are all assemblies of more general cognitive processes. To borrow a phrase from Liz Bates, both language and music might be viewed as "new machine[s] constructed entirely out of old parts" (Bates & MacWhinney, 1989, p. 10). By this second theory, there may be few (or even no) processes specific to linguistic or musical parsing per se; instead both may recruit an assembly of more basic underlying cognitive mechanisms to deal with similar cognitive demands. This debate has a long and sometimes acrimonious history; however, both theoretical approaches will benefit from more specific theories of the cognitive demands imposed by musical and linguistic structure, data from more sophisticated experimental techniques (e.g., Grahn, 2012), and insights from developmental perspectives (cf. Brandt et al., 2012; Hannon & Trainor, 2007; McMullen & Saffran, 2004).

Music and language are complex, multifaceted systems, and research on their relationship is beginning to go beyond questions of shared versus distinct processing to question which specific aspects of structural processing in music and language recruit shared cognitive and neural systems, and what those systems might be. We believe this change in focus is important and that a deeper understanding of the cognitive and neural basis of these domains is impossible without moving away from monolithic conceptions of "music" and "language." Instead, we advocate a reductionist approach to investigate the specific cognitive demands imposed by different aspects of music and language and/or imposed by any other type of complex cognitive system. We take a step in this direction by proposing that the ability to flexibly control our behavior and cognition (i.e., cognitive control) plays a critical role in resolving conflict and allowing for reinterpretation in both music and language.

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