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# Syntax in music and language: The role of cognitive control

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## Abstract

The relationship between structural (or syntactic) processing in music and in language is not yet clear. Evidence indicating that these two processes are shared conflicts with other results suggesting that they are largely distinct. These conflicting findings suggest that musical and linguistic processing may share some, but not all, underlying processes, raising the question of what exactly those shared processes might be. Two experiments tested the idea that one shared process is *cognitive control* by pairing manipulations of musical structure with the Stroop task, a standard test of cognitive control. Manipulations of harmonic expectancy, but not of timbral expectancy, interacted with Stroop interference effects, suggesting that cognitive control is at least one specific process underlying shared syntactic processing in music and language.

**Keywords:** cognitive control; music and language; musical syntax

## Introduction

Interest in the relationship between music and language has a long history, dating back at least to Darwin (1871). Over the last several years, a more specific focus on the relationship between structural (or syntactic) processing in music and language has received increasing attention (for recent reviews, see Patel, 2008; Slevc, 2012; Tillmann, 2012). This likely is due, at least in part, to an influential proposal about the relationship between structural processing in language and music: Patel's (2003) *shared syntactic integration resource hypothesis* (SSIRH; see also Patel, 2008). The SSIRH proposes that music and language involve separate representations (e.g., nouns and verbs in language, tonal functions in music), but recruit a shared set of cognitive resources that are required to integrate these separate representations into evolving sequences.

There is a growing body of evidence supporting the SSIRH. Much of this evidence comes from experiments using 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 (vs. additive effects, which would indicate independent processes). For example, an

electrophysiological response characteristic of a violation of linguistic syntax (the left anterior negativity, or LAN) is reduced when linguistic syntactic violations are paired with a concurrent music-syntactic irregularity (Koelsch, Gunter, Wittfoth, & Sammler, 2005). Similarly, sung complex sentences are especially difficult to understand when critical regions are sung out-of-key (Fedorenko, Patel, Casasanto, Winawer, & Gibson, 2009).

Other behavioral evidence comes from on-line sentence processing paradigms, where readers' slowed processing of temporary syntactic ambiguities is especially pronounced when the disambiguating word is paired with a harmonically unexpected chord (Slevc, Rosenberg, & Patel, 2009; also see Hoch, Poulin-Charronnat, & Tillmann, 2011, for related findings). More specifically, Slevc et al. (2009) relied on *garden path effects*, where readers are slower to comprehend the disambiguating word *was* in a sentence like "*The scientist proved the hypothesis was false*" compared to an unambiguous context like "*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. 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, such an interaction did not emerge for semantically unexpected words (e.g., *pigs* as a continuation of "*The mailman was afraid of...*") suggesting that the interactive processes are specific to syntax. However, a more recent finding casts doubt on this last conclusion: the same harmonic manipulations did lead to interactive effects when paired with sentences containing "semantic garden paths" such as "*The old man went to the bank to withdraw his net which was empty*" (Perruchet & Poulin-Charronnat, 2013). Thus it seems that these interactive effects (and the shared integration resource of the SSIRH) may not be specific to syntactic processing per se.

In addition, some recent neuroimaging studies have not found substantial overlap between neural regions implicated in the processing of language and music (Fedorenko, Behr,

& Kanwisher, 2011; Rogalsky, Rong, Saberi, & Hickok, 2011). These studies compared a linguistic contrast (activation to intact sentences versus non-words or versus jabberwocky sentences) to a musical contrast (activation to intact music versus scrambled music or versus silence), and found little evidence for shared regions implicated in both contrasts.

These conflicting findings raise the question: what kind of shared process links musical structural processing to some aspects of linguistic processing (including syntactic errors, syntactic complexity, and both syntactic and semantic garden paths), but *not* to other aspects such as the processing of semantically surprising words and the difference between intact and scrambled sentences? One way to characterize this distinction is that the aspects of language processing that are related to musical structure require not only the processing of an unexpected element, but also the resolution of conflict between this unexpected information and a current representation of an incrementally constructed (and/or predicted) structure. The unrelated aspects of language, in contrast, may not place demands on conflict resolution *per se* as there is no obvious way to resolve a semantic anomaly or a scrambled sentence.

This sort of conflict detection and resolution process is termed *cognitive control*, referring broadly to the cognitive processes that allow for the regulation of mental activity required to resolve competing representations (see, e.g., Miller & Cohen, 2001). Cognitive control processes have been implicated in various aspects of language processing, including parsing of garden path sentences and semantic plausibility effects (see Novick, Trueswell, & Thompson-Schill, 2010, for a recent review), and it is possible that the types of linguistic manipulations that interact with musical structure are of this general type. By this account, 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) might reveal simultaneous use of cognitive control resources.

This account implies that musical syntactic processing—at least as measured in the studies cited above—also relies on cognitive control mechanisms. Indeed, this is likely to be the case. Listening to music involves building up complex cognitive representations of musical structure. This not only involves processing and integrating musical elements as they occur, but also incrementally generating and evaluating predictions based on implicit knowledge of musical structure (see Rohrmeier & Koelsch, 2012, for discussion). One hazard of this predictive processing is that new information can be inconsistent with one's prediction, thus harmonic processing requires the ability to both detect conflict between predicted and observed precepts and the ability to resolve this conflict by overriding and updating an evolving representation of musical structure. Conflict between musical precepts and predictions likely arises in many situations, not the least of which are cases of musical ambiguity (e.g., musical garden paths; Temperley, 2001).

One form of indirect evidence for a role of cognitive control in musical syntax comes from neuroimaging findings. Regions in the inferior frontal gyrus (including Broca's area) that are linked to cognitive control processes (both generally and in language processing; e.g., Miller & Cohen, 2001; Novick et al., 2010) have also been implicated in neuroimaging studies of musical syntactic processing (albeit more bilaterally or even right lateralized; e.g., Maess, Koelsch, Gunter, & Friederici, 2001; Tillman, et al., 2006).

A second form of indirect evidence for a role of cognitive control in musical syntactic processing comes from evidence that musical training is associated with advantages in cognitive control ability (Bialystok & DePape, 2009; Pallesen et al., 2010) among other types of cognitive advantages (e.g., Schellenberg, 2006). A musician advantage in cognitive control could plausibly result from the additional demands placed on cognitive control mechanisms from extensive musical training and practice, but only if those demands tax (and thus potentially strengthen) cognitive control processes.

## Current experiments

The aim of the experiments reported here was to provide a direct test of whether cognitive control mechanisms are involved in musical syntactic processing (as has been argued to be the case for linguistic syntactic processing). If cognitive control processes are, in fact, an important part of musical syntactic processing, less expected chords should impose relatively greater demands on cognitive control. Assuming cognitive control is a limited-capacity resource, this should lead to a temporary reduction in the ability to exercise cognitive control in other tasks.

In order to measure demands on cognitive control, we turned to a prototypical cognitive control task: the Stroop task (Stroop, 1935; see McLeod, 1991, for a review). In the standard Stroop task, participants must name the ink (or font) color of printed stimuli. These stimuli can be of three types: *congruent*, where the printed word is the same as the to-be-named ink color (e.g., the word "GREEN" printed in green font), *incongruent*, where the printed word is a different color name than the to-be-named ink color (e.g., the word "BLUE" printed in green font), and *neutral* (e.g., the string "####" printed in green font). Cognitive control demands are reflected in *Stroop interference*, where responses are slower to incongruent than to neutral trials. The Stroop task can also yield *Stroop facilitation*, reflected in faster responses to congruent than neutral trials, however these facilitative effects are not generally assumed to result from demands on cognitive control.

Because Stroop interference is a prototypical measure of cognitive control, it can be used as an index of cognitive control demands at a given moment. The experiments presented below do just this by investigating if, and how, Stroop interference is affected by a concurrent musical syntactic manipulation.

## Experiment 1

In Experiment 1, participants performed a standard Stroop task while hearing musical chorales. The primary question was whether the harmonic expectancy of a chord occurring during a trial of the Stroop task would influence Stroop interference effects.

### Method

**Participants** Twenty-five undergraduate students from the University of Maryland participated in exchange for course credit. Participants were unselected with regard to musical training.

**Materials** Stimuli for the Stroop task were the strings “RED”, “GREEN”, “BLUE”, or “XXXX”. The word stimuli appeared half of the time in a congruent color (e.g., the word “BLUE” in blue font) and half of the time in an incongruent color (e.g., “BLUE” in green or red font); the neutral (“XXXX”) stimuli appeared equally often in each of the three font colors. Because the primary effect of interest here is in Stroop interference (vs. facilitation), congruent trials were treated as fillers and excluded from analysis.

Musical stimuli were twelve six-chord chorales based on Western musical structure, half in major and half in minor keys. Each chorale ended either on a tonic chord (the tonal center of the chorale’s key) or ended on a chord belonging to another key, and thus was either harmonically expected or unexpected (see Figure 1 for an example). In addition, each chorale occurred once more as a filler item; these fillers ended on a variety of chords. While these fillers were generally harmonically unexpected, they were not constructed in a theoretically constrained way and so were excluded from analyses. (Note, however, that treating these fillers as harmonically unexpected trials does not substantially alter the main pattern of results.)

The figure consists of two main panels. The top panel shows musical notation for two conditions, A and B. Condition A shows a six-chord sequence ending on a tonic chord. Condition B shows a six-chord sequence ending on a chord from a different key. The bottom panel shows a computer monitor displaying two options: i) BLUE and ii) XXXX. A timeline arrow points to the right below the monitor.

Figure 1: Example stimuli in Experiment 1. The top panel shows an example musical chorale ending in a harmonically expected tonic chord (A) or a harmonically unexpected chord from a different key (B). The bottom panel represents the incongruent (i) or neutral (ii) visual target for the primary color response task.

**Procedure** Participants were tested individually on iMac computers using PsychoPy software (Pierce, 2007). The primary task was to respond to the color of the visual stimuli (red, green, or blue) by pressing a corresponding button (the left, down, or right arrow, respectively). These color/button mappings were presented on the screen during the entire task. Participants first performed a practice block of twenty-one color-naming trials (without concurrent musical stimuli) to learn the color/key mappings, then a second practice block of ten trials where the target stimulus appeared at the onset of the final chord of a six-chord chorale (all practice chorales ended on the tonic). Finally, participants performed the experimental block consisting of 72 chord sequences ending on the tonic, 36 chord sequences ending on a harmonically unexpected chord, and 36 filler sequences. Within each musical condition, one third of the trials were neutral, one third were incongruent, and one third were congruent (filler) trials.

A schematic of the four conditions for an individual experimental trial is shown in Figure 1.

**Design and analysis** Response times were log-transformed and analyzed using linear mixed-effects models in the statistical software R (version 2.15.2; R Development Core Team, 2012). Stroop trial type (*text condition*: incongruent or neutral) and the harmonic role of the final chord (*harmonic condition*: expected or unexpected) were entered as fixed effects using orthogonal contrast coding. The fully specified random effect structure was included for both participants and items (see Barr, Levy, Scheepers, & Tily, 2013), but random effects are not reported as only fixed effects were of theoretical interest. The current implementation of lme4 does not compute  $p$  values for models that include random slopes, therefore we follow Gelman and Hill (2007) by assuming that any absolute  $t$  value greater than 2 indicates a significant effect.

### Results

A significant main effect of text condition ( $b = -0.24$ ,  $SE = 0.029$ ,  $t = -8.23$ ) revealed (unsurprisingly) that responses were slower for incongruent than neutral strings. There was not a significant main effect of harmonic condition ( $b = -0.0048$ ,  $SE = 0.022$ ,  $t = -0.22$ ), however a significant interaction between harmonic condition and text condition ( $b = -0.10$ ,  $SE = 0.042$ ,  $t = -2.39$ ), revealed that the Stroop interference effect was significantly larger when accompanied by an unexpected final chord. The Stroop interference effects in the harmonically expected and unexpected conditions are plotted in Figure 2.

### Discussion

Experiment 1 found larger Stroop interference effects when Stroop trials occurred during structurally unexpected chords, suggesting that the processing of harmonically unexpected chords involves an underlying process that is shared with Stroop interference. This bolsters theoretical reasons to expect cognitive control processes to play a role in musical

syntactic processing and adds to previous indirect evidence for such a relationship, such as (bilateral) inferior frontal activation associated with musical syntax (e.g., Tillmann et al., 2006) and cognitive control advantages associated with musical training (e.g., Bialystok & DePape, 2009).

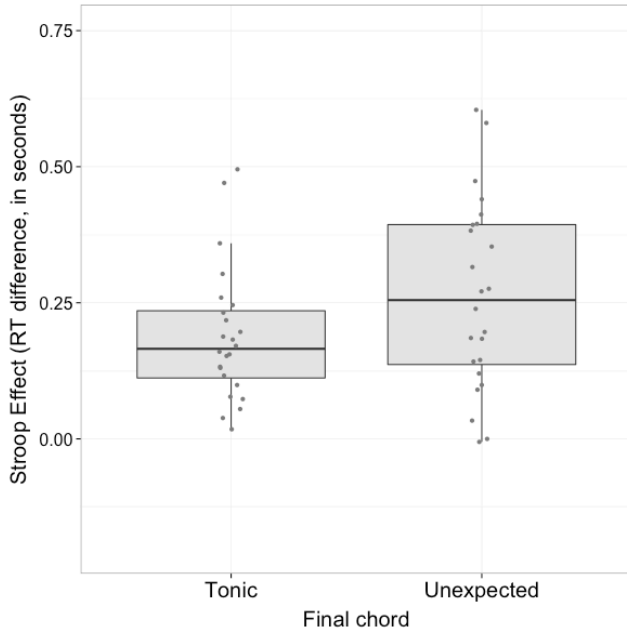


Figure 2: Stroop interference (incongruent minus neutral) by the harmonic condition of the final chord (the tonic chord or an unexpected chord from another key) in Experiment 1. Data are plotted as untransformed means of participant means and dots indicate individuals' scores.<sup>1</sup>

A counter explanation for these results might be that the harmonically unexpected chord drew attention away from the primary task of responding to font colors, thus leading to an exaggerated effect of incongruent trials due not to shared mechanisms, but simply to surprise or distraction. It is not obvious that simple distraction would enhance the Stroop effect as this distraction would presumably affect neutral as well as incongruent trials. However it is nevertheless possible that some aspect of the musical manipulation besides its harmonic unexpectedness is responsible for the observed interaction. Experiment 2 aimed to address this possibility by using a noticeable, but not music-syntactically relevant, manipulation of *timbre*, or sound quality.

## Experiment 2

If the interaction between Stroop interference and harmonic expectancy found in Experiment 1 results from surprise or distraction, then similar results should emerge when another type of unexpected auditory event occurs, even if that event

<sup>1</sup> For ease of interpretation, Figures 2 and 3 display means of participants' mean untransformed RTs; note, however, that analyses were conducted over non-averaged, log-transformed RTs.

does not require conflict resolution. If, on the other hand, the interaction observed in Experiment 1 reflects the role of conflict resolution processes, then such interactions should not arise unless the unexpected stimuli induces some degree of resolvable conflict with an incremental and predictive cognitive representation of musical structure.

To examine these possibilities, Experiment 2 employed the same design as Experiment 1, but instead of manipulating musical syntactic expectancy, manipulated musical timbre (cf. Slevc et al., 2009). In contrast to the harmonic manipulation in Experiment 1, where an unexpected chord could reflect some kind of resolvable modulation or other harmonic "twist," there is no obvious way to resolve an unexpected timbre. Thus, a chord of unexpected timbre (that plays an expected harmonic role) should not lead to conflict resolution processes, and should not interact with the Stroop interference effect.

A chord of unexpected timbre should, however, be at least as surprising and attention demanding as an out-of-key chord, so if the interaction observed in Experiment 1 results from surprise or distraction, the same pattern of results should emerge in Experiment 2.

## Method

**Participants** Thirty undergraduate students from the University of Maryland participated in exchange for course credit or for a small (\$5) payment. As in Experiment 1, participants were unselected with regard to musical training.

**Materials and Procedure** The visual stimuli in Experiment 2 were identical to those in Experiment 1. The musical chorales were also identical except for the final chords in the unexpected conditions, which were always the tonic chord (thus always harmonically expected) but varied in terms of their *timbre*. Specifically, the final chord was either of the expected piano timbre, i.e., the same timbre as the rest of the chorale, or was played in a distinct timbre (the *sitar* timbre, as implemented in MuseScore version 1.2). An additional set of trials ended with a timbre only slightly different from the rest of the chorale (MuseScore's *ukulele* timbre, which sounds remarkably similar to a piano); as in Experiment 1, these intermediate trials were treated as fillers and not included in the analysis.

**Design and Analysis** Response times were analyzed just as in Experiment 1. Experiment 2 crossed the fixed-effects factors of *text condition* with *timbral condition* (expected or unexpected timbre) with the maximal random effects structure supported by the data.<sup>2</sup>

## Results

As in Experiment 1, participants were reliably slower to respond to the color during incongruent trials than

<sup>2</sup> The by-item random slopes for timbral condition and the timbral condition by text condition interaction had to be removed for the statistical model to converge.

congruent trials (i.e., a significant effect of text condition;  $b = -0.17$ ,  $SE = 0.023$ ,  $t = -7.14$ ). There was no significant effect of the timbre of the final chord ( $b = 0.20$ ,  $SE = 0.14$ ,  $t = 1.42$ ) and, unlike in Experiment 1, no interaction between these factors ( $b = -0.16$ ,  $SE = 0.029$ ,  $t = -0.55$ ). The Stroop interference effects in the timbrally expected and unexpected conditions are plotted in Figure 3.

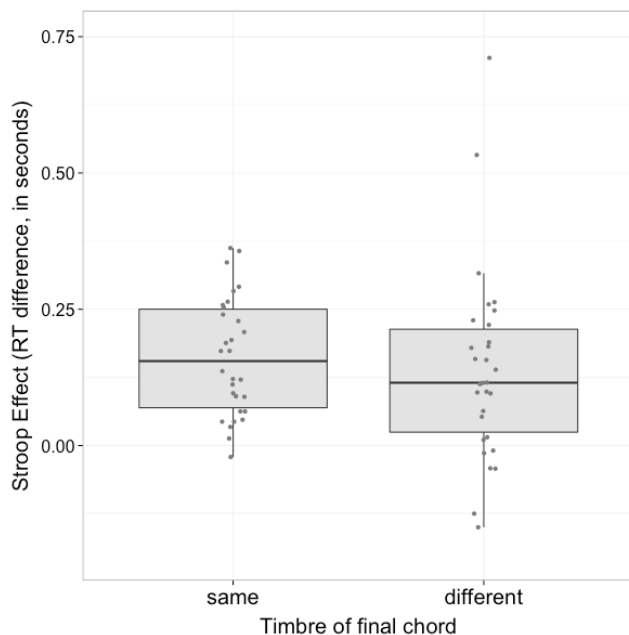


Figure 3: Stroop interference (incongruent minus neutral) by the timbral expectancy of the final chord (same vs. different timbre) in Experiment 2. Data are plotted as untransformed means of participant means and dots indicate individuals' scores.

## Discussion

Experiment 2 showed a standard effect of Stroop interference, but this effect did not interact with the timbre of a concurrent (tonic) chord. If anything, the average magnitude of the Stroop interference effect was numerically smaller in the unexpected timbre condition. This suggests that the interactive effects found in Experiment 1 did not result simply from the attention capturing nature of the unexpected stimuli, but were rather a function of the need to resolve conflict between the final chord and its expected harmonic role.

### General Discussion

The experiments reported here tested the idea that the processing of musical structure relies on general cognitive processes of cognitive control, which are also thought to underlie aspects of language processing. Experiment 1 crossed a standard cognitive control task—the Stroop task—with a manipulation of harmonic expectancy, and found interactive effects: Stroop interference was exacerbated when accompanied by a structurally unexpected chord.

Experiment 2 showed that this interaction between harmonic expectancy and Stroop interference was not simply due to distraction or divided attention as such an effect did not emerge when Stroop trials were paired with chords of an unexpected timbre.

The interactive effects in Experiment 1 are perhaps especially notable as there was no musical task requiring participants to pay attention to the musical chorales, and participants were an unselected group of undergraduate students, not a group of musicians. These observations suggest that these effects do not depend on any particularly effortful type of musical processing, but instead reflect the broad knowledge of musical syntax that arises simply through a lifetime of exposure to a specific musical tradition (cf. Bigand & Poulin-Charronnat, 2006).

These findings support the theory that cognitive control does, in fact, underlie at least some of the shared processing resources implicated in linguistic and musical syntax. A further implication is that the processing of both music and language should overlap to some extent with a variety of other domains that also rely on these general mechanisms of cognitive control (not just simple cognitive tasks like the Stroop task). There is already evidence for some such relationships; for example, interactive effects have been demonstrated during simultaneous processing of music and arithmetic (Hoch & Tillmann, 2012). In addition, “action syntax” or “scripts” (i.e., meaningful structured representations of action sequences) may be related to both linguistic syntax (e.g., Farag et al., 2010) and to musical syntactic processing (Harding et al., 2011).

These relationships between different types of structural processing – be those structures musical, linguistic, mathematical, or action schemas – are not likely to reflect a syntax-specific shared underlying process. Instead, these processes likely draw on the same cognitive mechanisms to deal with similar demands, and these data suggest that one such mechanism is cognitive control. Of course, it is unlikely that the relationship between structural processing in language and music reflects *only* cognitive control mechanisms. Musical and linguistic structure are rich and complex systems that surely draw on a variety of cognitive mechanisms. Nevertheless, these data take a step towards a more specific account of exactly what sort of shared integration resources might underlie linguistic and musical syntax by implicating the well-studied cognitive construct of cognitive control.

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