Atten Percept Psychophys
DOI 10.3758/s13414-015-1042-y

Inharmonic music elicits more negative affect and interferes more with a concurrent cognitive task than does harmonic music

Tanor Bonin[1] · **Daniel Smilek**[1]

Abstract We evaluated whether task-irrelevant inharmonic music produces greater interference with cognitive performance than task-irrelevant harmonic music. Participants completed either an auditory (Experiment 1) or a visual (Experiment 2) version of the cognitively demanding 2-back task in which they were required to categorize each digit in a sequence of digits as either being a target (a digit also presented two positions earlier in the sequence) or a distractor (all other items). They were concurrently exposed to either task-irrelevant harmonic music (judged to be consonant), task-irrelevant inharmonic music (judged to be dissonant), or no music at all as a distraction. The main finding across both experiments was that performance on the 2-back task was worse when participants were exposed to inharmonic music than when they were exposed to harmonic music. Interestingly, performance on the 2-back task was generally the same regardless of whether harmonic music or no music was played. We suggest that inharmonic, dissonant music interferes with cognitive performance by requiring greater cognitive processing than harmonic, consonant music, and speculate about why this might be.

Keywords Dissonance · Inharmonicity · Music · Auditory perception · Cognitive performance · Distraction

✉ Tanor Bonin
tanorbonin@gmail.com

[1] Department of Psychology, University of Waterloo, 200 University Ave. West, Waterloo, ON N2L 3G1, Canada

Introduction

Despite its ubiquity in musical contexts, *dissonance* remains an enigmatic musical phenomenon. Lacking a singular definition in the music theory and music cognition disciplines (cf., Cazden, 1980; Tenney, 1988), dissonance can readily be construed as a phenomenology (Johnson-Laird, Kang, & Leong, 2012) characterized by negative affect and an awareness of structural incoherence within the music (McLachlan, Marco, Light, & Wilson, 2013). It is integral to the musical expressions of *tension, worry, unrest* (Costa, Bitti, & Bonfiglioi, 2000), and general musical *unpleasantness,* and is widely regarded as the functional counterpart of musical *consonance*— a phenomenological appraisal of musical *stability, resolution,* and *pleasantness* (Bigand, Parncutt, & Lerdahl, 1996; Blood, Zatorre, Bermudez, & Evans, 1999; Cook & Fujisawa, 2006; Malmberg, 1918; McDermott, Oxenham & Lehr, 2010; Zentner & Kagan, 1998). Expert composers are seemingly those who can strike the delicate balance between dissonance and consonance to guide the listener through the desired musical landscape (Bidelman & Heinz, 2011; Krumhansl, 1990). As the Grammy award-winning producer and composer Quincy Jones said: "Music in movies is all about tension and release, dissonance and consonance" (Farndale, 2010). While composers, musicians, and listeners alike are typically most interested in the emotive capacity of dissonance (cf., Juslin & Västfjäll, 2008), little is known about the associated cognitive demands that dissonance places on the listener. We address this latter inquiry in our current research. In particular, our goal is to examine whether dissonant music interferes with cognitive performance to a greater extent than consonant music.

There are good reasons to believe that dissonant music might produce more cognitive interference than consonant music. First, dissonant music involves conflicting sensory

Published online: 29 December 2015

information that consonant music does not. While consonance generally arises from simple harmonic acoustic frequencies, dissonance is associated with complex inharmonic frequency spectra (Pythagorus re: Helmholtz, 1863; Hutchinson & Knopoff, 1978; Kameoka & Kuriyagawa, 1969a, 1969b; McDermott, Lehr, & Oxenham, 2010; Tenney, 1988). Inharmonic frequencies produce frequency modulations (FM) known as “beating” and “roughness” within the critical bands of the basilar membrane (Plomp & Levelt, 1965; Terhardt, 1974; Yost, 2008), and noisier neural signals within the sensory efferents of the auditory brainstem (Bidelman & Heinz, 2011). This sensory complexity might impose greater demands on the listener’s cognitive processes than the simpler harmonic content of consonant music.

Second, cultural (Cazden, 1980; Fritz et al., 2009; Lundin, 1947; Vassilakis, 2005) and music-theoretical (Krumhansl, 1990) norms restrict the prevalence of inharmonic intervals within most tonal music repertoires (Huron, 1994), making dissonant moments unexpected and *bewildering* relative to their consonant counterparts (Costa, Bitti, & Bonfiglioli, 2000). This bewildering quality of dissonant music might further contribute to the information complexity of dissonant intervals, producing cognitive demands on the listener that consonant, harmonic music does not. Consistent with these possibilities is a large body of literature showing that behavioral responses to complex (Patten, Kircher, Oslund, & Nilsson, 2004), ambiguous (MacDonald, Just, & Carpenter, 1992), conflicting (Eriksen & Eriksen, 1974; MacLeod, 1991; Sarmiento, Shore, Milliken & Sanabria, 2012; Stroop 1935), and unexpected (Crump, Gong, & Milliken, 2006, Jonides 1981; Posner, Snyder, & Davidson, 1980;) stimuli take more time and are often less accurate than responses to simple, unambiguous, non-conflicting, and expected stimuli.

Third, dissonance entails negative affective evaluations, and this negative affect might lead to impaired performance on cognitive tasks. This possibility is consistent with a large body of literature showing that stimuli perceived with negative emotional valance capture attention and disrupt performance on ongoing tasks (e.g., Eastwood, Smilek & Merikle, 2003; Fenske & Eastwood, 2003; Koster, Crombez, Van Damme, Verschuere & De Houwer, 2004; Maratos, Mogg & Bradley, 2008; Öhman, Flykt & Esteves, 2001; Öhman, Lundqvist, & Esteves, 2001). It is worth noting, however, that there are also exceptions to this finding (e.g., Dreisbach & Goschke, 2004; Smoski et al., 2008; von Helversen, Wilke, Johnson, Schmid & Klapp, 2011), precluding any strong predictions on the basis of affective valence. Nevertheless, there remains the possibility that the negative emotional dimension of dissonant music might impair performance on concurrent cognitive tasks more than the positive emotional dimension of consonant music.

Fourth, it has been hypothesized that dissonance might interfere with cognitive processing more than consonance because the *tension* and *unfulfilled expectations* it creates lead to higher levels of arousal (Bodner, Gilboa, & Amir, 2007). This hypothesis assumes that the relation between arousal and performance on cognitive tasks can be represented with an inverted U-shaped curve (cf., Easterbrook, 1959), with the lowest and highest levels of arousal leading to poorer cognitive performance than the intermediate levels of arousal that lead to optimal cognitive performance. Specifically, Bodner et al. (2007) suggested that, by violating musical expectations, dissonant music might push arousal levels to the extreme high end of the arousal curve where performance decrements are typically observed (Bodner, Gilboa, & Amir, 2007).

Lastly, studies of the irrelevant sound effect (ISE; see Banbury, Macken, Tremblay & Jones, 2001; Hughes & Jones, 2001; Ellermeier & Zimmer, 2014 for reviews) have examined the psychoacoustic properties of sounds that influence primary task completion. Particularly relevant to the present focus is the finding that staccato music interferes with primary task completion more than does legato music, presumably as the result of its more salient state changes relative to those in legato music (Schlittmeier, Hellbrück, & Klatte, 2008). Based on this finding, one might expect dissonant stimuli to produce greater cognitive interference than their consonant counterparts if they contained more salient state changes. In addition, a recent computational model of the ISE has demonstrated that the distractibility of both musical and non-musical sounds is readily predicted by their low frequency fluctuation strengths (of FM up to 4 Hz; Schlittmeier, Weißgerber, Kerber, Fastl, & Hellbrück, 2012). At first glance, one might expect that the interference occurring at low FM frequencies might generalize to the high FM frequencies characteristic of the beating and roughness phenomena we have noted above that often accompany musical dissonance (cf., Plomp & Levelt, 1965). However, investigations of the ISE produced by tones with FM frequencies between 10 Hz and 50 Hz (i.e., within the range of audible beating and roughness, see Plomp & Levelt, 1965) demonstrate no measurable interference with cognitive performance (Ellermeier & Zimmer, 2014). It thus remains unclear whether and how dissonant music might produce greater cognitive interference than consonant music on the basis of the extant ISE literature.

For all of the aforementioned reasons, dissonant music might reasonably be expected to impair performance on concurrent cognitive processing to a greater extent than consonant music. To date, the results regarding the influence of musical consonance-dissonance on performance of cognitive tasks have been mixed, and the available evidence falls shy of demonstrating that dissonant music impairs cognitive processing to a greater extent than consonant music.

For instance, while Bodner, Gilboa, and Amir (2007) expected dissonant music to induce greater interference on concurrent cognitive tasks compared to consonant music or no music, they surprisingly found no evidence to support their expectation. In fact, under some conditions they found performance to be best while dissonant music was played. Specifically, participants performed *better* on simple cognitive tasks such as the Letter Cancellation Task (LCT) and the Adjective Recall From a Story (ARS) task when exposed to dissonant music compared to consonant music or no music. Additionally, when completing the hardest task (Adjective Recall From a List; ARL) participants performed worse while listening to music compared to completing the task in silence, but there were no performance differences between the consonant and dissonant listening conditions. Though contrary to their predictions, the authors interpreted the performance benefits associated with exposure to dissonant music as a result of increased arousal and task engagement. They suggested that the dissonant music elicited enough arousal to promote optimal performance in the easier tasks (LCT and ARS), while the consonant music and no-music conditions elicited insufficient arousal and suboptimal cognitive performance. Addressing the results of the most difficult task (the ARL), the authors suggested that both consonant and dissonant music elicited too much arousal relative to no music, leading to equally poor performance between the consonant and dissonant conditions and relatively better performance in the no-music condition (Bodner, Gilboa, & Amir, 2007, pg. 300).

Some pieces of evidence consistent with the idea that dissonant music might negatively impact performance on specific cognitive tasks relative to consonant music comes from a recent study by Masataka and Perlovsky (2013). Participants in this study listened to consonant or dissonant music while at the same time completing neutral (colored strings of Xs) and incongruent Stroop trials. While musical dissonance did not influence performance on the neutral Stroop trials, participants responded more slowly and less accurately to incongruent Stroop trials when dissonant music was played than when consonant music was played. These findings led the authors to suggest that the interfering effect of musical dissonance manifests *only* when an individual is faced with a task that requires the resolution of incompatible cognitions, such as the incompatible response demands of the word-color information of incongruent Stroop trials. In other words, according to Masataka and Perlovsky (2013), musical dissonance has a very specific and targeted impact, restrictively hindering performance on tasks that involve a specific type of incompatibility, which they refer to as “cognitive dissonance” (Masataka & Perlovsky, pg. 5).

While Masataka and Perlovsky’s (2013) conclusion that musical dissonance influences only tasks that involve incompatible cognitions is certainly consistent with their findings, there remains the alternative possibility that musical dissonance might have a more general effect on cognitive processing. Specifically, the findings are also consistent with the view that dissonant music has a more general effect on cognitive performance via its general need for processing demands, its arousing effects, and its emotional valance, and that this interference is simply more pronounced as the cognitive processing demands of any given primary task increase. Critically, according to this view, musical dissonance should influence performance on any sufficiently demanding cognitive task, even if that task does not involve the specific sort of response selection conflict typified by incongruent trials on the Stroop task. Applying this more general view to the findings reported by Masataka and Perlovsky (2013), musical dissonance would have affected performance on incongruent Stroop trials and not neutral Stroop trials because incongruent trials are more cognitively demanding than neutral trails. It has yet to be shown, however, that dissonant music could impair performance to a greater extent than consonant music on a general cognitive task that does not involve response selection conflict, or, as Masataka and Perlovky (2013) put it, “cognitive dissonance.”

Building on the previous studies examining the link between musical dissonance and task performance, here we seek to demonstrate that task-irrelevant dissonant music produces more interference with concurrent cognitive processing than task-irrelevant consonant music. We reasoned that this interference should be most strongly evident during a sufficiently demanding cognitive task, where the potential effects of sensory complexity, enculturation, negative affect, and arousal might be most readily observed. In addition, as an attempt to generalize the findings from the Masataka and Perlovsky (2013) study, we wanted to challenge the assertion that dissonance only interferes with tasks that entail response selection conflict. Instead we posit that dissonance might pose a broad interference with cognitive processing, and here employ a 2-back task that requires active cognitive processing, like incongruent Stroop trials, but does not entail response selection conflict, unlike incongruent Stroop trials. Finally, we took care to tightly control the spectral characteristics of our musical stimuli, manipulating their position on the continuum of consonance and dissonance solely on the basis of their *harmonicity.* Isolating this spectral component allowed for targeted interpretations of our results that might relate to the differential spectral characteristics of our stimuli, and provided an acoustic basis for comparing our results with those of potential future investigations of the cognitive effects of dissonant music. Participants’ phenomenological appraisals of each stimulus were used to confirm that our acoustic manipulation produced the desired psychological effects.

Participants in our experiments were required to complete either an auditory (Experiment 1) or a visual (Experiment 2) version of the 2-back task—a sustained cognitively demanding task often used as an indicator of working memory capacities (Owen, McMillan, Laird, & Bullmore, 2005). In the 2-back task, participants are presented with a stream of digits and are required to press one response key when the presented digit matches the digit presented two positions earlier in the sequence (i.e., the digit is a target), and a different response key in all other cases (i.e., the digit is a distractor). While completing this primary task, participants were presented either with no distractions (no music), task-irrelevant harmonic (consonant) music, or task-irrelevant inharmonic (dissonant) music. We expected to find poorer performance on the primary 2-back task when participants were simultaneously presented with inharmonic music compared to when they were presented with harmonic music.

Experiment 1

Introduction

The purpose of Experiment 1 was to evaluate whether inharmonic music interferes with performance on a continuous and difficult cognitive task to a greater extent than does harmonic music. Participants were presented a sequence of numbers for the 2-back task in one ear with no music entering the other ear, or while simultaneously presented with task-irrelevant music (either harmonic or inharmonic) in the other ear. When music was present, participants were instructed to attend to the numbers of the 2-back task and to ignore the music. In our version of the 2-back task, the sequence of numbers contained infrequent targets, which were defined (and described to participants) as a digit in the sequence that was also presented two trials earlier in the sequence. All of the remaining numbers in the sequence were distractors. Participants were required to respond to every number, pressing one response key with one hand when a target number was presented and a different key with the opposite hand when a distractor number was presented. This allowed us to measure performance accuracy (in terms of sensitivity, derived from hits and false alarms), as well as response times (RTs) to both target and distractor numbers. If inharmonic music interferes with the task to a greater extent than does harmonic music, then performance (in terms of accuracy and RT) on the 2-back task should be poorer when inharmonic music is played concurrently compared to when harmonic music is played.

Although our primary focus was on comparing cognitive performance while participants were exposed to harmonic and inharmonic music, we also decided to measure performance on the auditory 2-back task in the absence of any musical distraction. Analyses of these data allowed us to compare performance on the 2-back task when no music was played with performance when either harmonic or inharmonic music was played. No *a priori* predictions were made with regard to these comparisons.

Finally, we had participants provide phenomenological appraisals of the harmonic and inharmonic musical stimuli after the experimental block in which they heard each musical stimulus. These allowed us to confirm that our spectral manipulations had the desired effects on the participants' experiences of consonance and dissonance. We expected that the inharmonic music would be rated as more unpleasant and more dissonant than the harmonic music.

Method

Participants

A sample size of 48 participants was predetermined for Experiment 1 before data collection began based on the results of a small pilot study (N = 30).[1] Forty-eight undergraduate students (mean age = 19.51 years, SD = 1.82 years; 16 male) from the University of Waterloo were included in the final analysis. The students participated in a 30-min experiment and were compensated with partial course credit. Participants were not selected on the basis of musical training, but the number of years of music lessons ranged from 1 to 17 years (mean = 6.18 years, SD = 4.59 years).

After completing data collection for an initial sample of 48 participants, the data from ten participants were excluded from the original data set for behavioral non-compliance (responding only to target trials, prematurely terminating the experiment, and one case where two data sets were discarded because a participant removed their headphones to instigate an unrelated conversation with another in the middle of the experiment). As a result, ten additional participants were recruited to complete the full counterbalance and reach the predetermined sample size of 48.

Apparatus

A Python (2.7.9; Van Rossum, 2007) script was written to create the auditory 2-back task, present the primary 2-back task stimuli and distracting musical stimuli, and record response data (physical keys pressed, accuracy of the responses, i.e., hits and false alarms, and RTs). Musical stimuli were recorded using Steinberg's Cubase 6 digital audio workstation, the Steinberg HalionSonic SE VST, a Samson Graphite 49 MIDI keyboard, and a Yorkville foot controller.

The experiment was conducted on an Apple Mac Mini with OS X 10.10.1 and a 2.6 GHz Core i7 processor. On-screen instructions and prompts for the phenomenological appraisals of the harmonic and inharmonic musical stimuli were presented on a 24-in. Phillips 244E monitor at a resolution of 1,920 × 1,080. Auditory stimuli were delivered through circumaural closed-back headphones (Sony MDR-MA100). The attended stream of numbers for the 2-back task and the distracting

[1] This pilot study was nearly identical to Experiment 1 presented here, with the exception that participants were not explicitly instructed to respond as quickly and accurately as possible.

music were quasi-controlled for loudness by equating RMS and LUFS amplitudes across conditions. Participants were exposed to the stimuli at comfortable hearing levels and were reminded that they should notify the experimenter if their listening experience became uncomfortable at any time.

Stimuli

Two-back task The stimuli for the 2-back task were nine simulated female voice recordings of the spoken numbers 1 through 9 created using Apple's Text to Speech application. The Python program then generated a pseudo-random sequence of these numbers with three constraints: First, 20 % of the numbers in the sequence were the same as the number that was presented two positions earlier in the sequence. These numbers served as the *targets* in the 2-back task (i.e., 20 % target rate). Second, targets were separated by at least four positions in the sequence, such that a target and the digit that occurred two digits prior to the target were never separated by another target digit. Third, each number was presented once, without repetition, before the first target digit occurred. Each participant received a different randomized sequence of the numbers, and it was this sequence that constituted the experiment's primary 2-back task. Two-back stimuli were presented with an stimulus onset asynchrony (SOA) of 2,500 ms.

Music The harmonic and inharmonic musical distractors were derivatives of a novel 8'10" piano performance by one of the authors (TB). The performance was conducted to a constant tempo of 70 beats/min, with various rhythmic permutations of 3/4 and 4/4 time. Beginning in C major, the performance modulated directly to A natural minor at 3'46" and modulated back to C major from 5'36"—5'49". The piece consisted of six unique contrapuntal voices (designated by pitch range and harmonic function, see Appendix), and the number of simultaneous voices varied from one to five throughout the duration of the piece. Mindful that particular beat densities and tempos potentiate particular states of arousal or emotional valence over others (e.g., Hevner, 1935, 1937; Peretz, Gagnon & Bouchard, 1998), the performer varied the tactus of the performance from quarter note pulses at its slowest (857.14 ms SOA) to triplet sixteenth pulses at its fastest (142.86 ms SOA).

The performance was recorded as MIDI data in Cubase 6. The original (recorded) MIDI data from this performance constituted the harmonic stimulus. The MIDI data from the original performance were then copied (including note velocities and pedal points) and pasted to separate tracks in Cubase 6 (one for each contrapuntal voice), where systemic pitch shifts were applied to each voice in order to create the inharmonic music. The Appendix provides a complete list of pitch shifts and interval changes. Both the harmonic and inharmonic stimuli shared a total frequency range between F1 (43.65 Hz) and E6 (1318.51 Hz). Thus, the two pieces were matched on virtually every sonic characteristic but their respective tonalities, with the octaves (unisons), major thirds, perfect fifths, major sixths, and major sevenths of the harmonic performance being performed as minor ninths, minor thirds, tritones (diminished fifths), minor sixths, and minor sevenths, respectively, between some voices of the inharmonic version.[2]

The MIDI data for both the harmonic and inharmonic stimuli were then submitted as triggers to the HalionSonic SE Yamaha S90ES piano sample bank. The HalionSonic SE VST produces panned stereo output to create a realistic acoustic image of its virtual instruments. In the specific case of the Yamaha S90ES piano, the lower piano notes are panned to the left of stereo midline and the higher notes are panned to the right of midline. Because we intended for our musical stimulus to be heard only from the participants' right auditory field, we exported the harmonic and inharmonic performances as mono wave files to ensure that they would retain their full spectral characteristics regardless of where they were panned during the experiment.

Procedure

After providing written consent, receiving a verbal briefing of the task instructions from the experimenter, and reading the on-screen instructions, participants first completed a practice block of the 2-back task consisting of 15 trials with three targets. During the practice trials, an error tone (Apple "blow.aiff") was presented if the participant made a mistake (miss or false alarm); this error tone was not present during the actual experimental trials. After completing the practice trials the participants were prompted to ask the experimenter for clarification or to ask any remaining questions concerning the task before continuing to the experiment proper.

The experiment proper was divided into three blocks, with one block corresponding to each of the three critical within-participant conditions in the study: Harmonic Music, Inharmonic Music, and No Music. The order of these blocks was counterbalanced across participants. Each block contained a to-be-attended auditory 2-back task with 39 targets among 196 spoken number stimulus trials (19.89 %). In all three blocks, the stream of numbers constituting the primary 2-back task was panned 90° left in stereo space and thus

[2] Our pitch manipulations resulted in virtually omnipresent inharmonicity in the inharmonic stimulus. For example, in the first 1'56" of the piece (34 bars; 132 beats), there was one beat containing a harmonic interval, and this happened to occur at a brief transition point in the piece where there were only two voices sounding. Furthermore, with a prevalence of only ~0.7 %, it might well be the case that those infrequent harmonic events were not even experienced as "consonant," as they would exhibit low pitch commonality with the surrounding pitches of the continuous inharmonic musical stream in which they are heard (cf., Bigand, Parncutt, & Lerdahl, 1996; Bigand & Parncutt, 1999). Thus we cannot only be confident that our selective pitch manipulations were successful in creating a (virtually) homogenously inharmonic stimulus, but also that these manipulations created a homogenously dissonant stimulus.

presented only to the participants' left ear. The musical stimuli in the Harmonic Music and Inharmonic Music blocks were panned 85° right in stereo space, thus perceived to be coming from the participants' right ear. The slight bias towards stereo midline for the musical distractors was chosen because it is known to reduce the saturation of a mono playback channel imposed by the low frequency audio content, thereby increasing signal clarity compared to full mono playback while imposing little influence on the perceived location of the sound source when both stereo channels are playing (White, 2000).

Before each block, participants were told whether or not they would hear music in the upcoming block. If music was to be presented, they were instructed to attend only to the number stream while ignoring the music. In the No-Music condition, participants were simply instructed to attend to the stream of digits. In all blocks, participants were instructed to respond as quickly and accurately as possible to all trials, pressing the "z" key with their left hand in response to targets, and the "/" key with their right hand in response to non-targets.

After the Harmonic Music and Inharmonic Music blocks, participants were prompted to complete a series of four phenomenological appraisals on the dimension of "pleasantness", "unpleasantness", "consonance", and "dissonance". Specifically, participants were asked: "On a scale from 1–7, how [Pleasant, Unpleasant, Consonant, Dissonant] was the music you just listened to?" Beneath the questions, participants were informed: "1 represents 'not at all' and 7 represents 'very'. " Participants responded by pressing one of the corresponding numbers on the keyboard. Participants were not given a formal definition of the terms 'consonant' and 'dissonant.'

Results

Phenomenological appraisals

Figure 1 shows the mean phenomenological appraisals of the harmonic and inharmonic music on each of the four dimensions (i.e., "Pleasant," "Unpleasant," "Consonant," and "Dissonant"). The mean appraisals for each dimension were submitted to a separate repeated measures two-tailed t-test. These tests revealed significant differences in ratings of the harmonic music and inharmonic music on all of the dimensions, with the inharmonic music being judged as less "pleasant," $t(1,47) = 7.816$, $p < 0.0001$, more "unpleasant," $t(1,47) = 6.239$, $p < 0.0001$, less "consonant," $t(1,47) = 3.601$, $p = 0.001$, and more "dissonant," $t(1,20) = 5.190$, $p < 0.0001$ than the harmonic music.

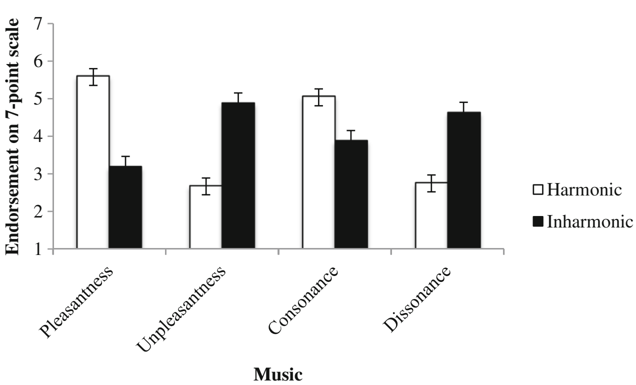

Fig. 1 Mean phenomenological appraisals of the harmonic and inharmonic music in Experiment 1 (n = 48). Larger numbers indicate greater experience of the rated dimension (1 = not at all, 7 = very). Error bars represent one standard error of the mean

Accuracy

Our accuracy analyses focused on the A' scores (shown in Fig. 2) derived from participants' hit rates and false alarm rates as per Macmillan and Creelman (2005). Table 1 presents the means of the hit rates and false alarm rates in the Harmonic Music, Inharmonic Music, and No-Music conditions for completeness. A customary omnibus ANOVA of A' scores considering Harmonic, Inharmonic and No Music as three within-participant levels of Music confirmed a main effect of Music, $F(1,47) = 10.910$, $p < 0.0001$. Our main interest was in the difference in A' between the Harmonic Music and the Inharmonic Music conditions. Accordingly, the mean A' scores in the Harmonic Music and the Inharmonic Music conditions for each participant were submitted to a repeated measures two-tailed t-test, which revealed that participants performed more poorly in the Inharmonic Music condition than in the Harmonic Music condition, $t(1,47) = 2.867$, $p = 0.006$ (mean difference = 0.022).

In addition, we conducted two repeated measures t-tests that compared mean A' scores in the No-Music condition with those in each of the Harmonic Music and Inharmonic Music conditions. The analyses showed that participants performed better in the No-Music condition relative to the Inharmonic Music condition, $t(1,47) = 3.66$, $p < 0.0001$ (mean difference = 0.031), and that there was no difference in A' scores between the No-Music condition and the Harmonic Music condition, $t(1,47) = 1.362$, $p = 0.180$ (mean difference = 0.009).

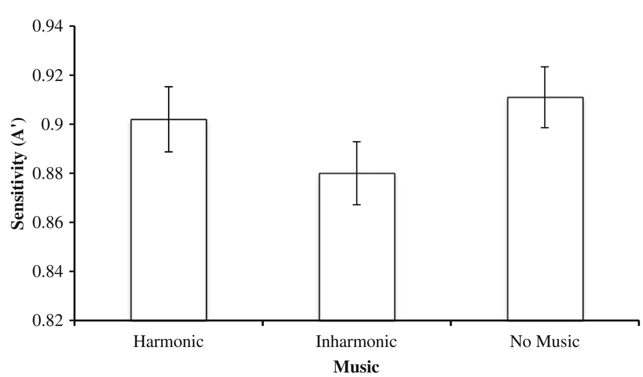

Fig. 2 Mean sensitivity (A') for each condition in Experiment 1 (n = 48). Error bars represent one standard error of the mean

Table 1 Mean hit rates and false alarm rates (and standard deviations) for each condition in Experiment 1 (n = 48)

Accuracy index	Music		
	Harmonic	Inharmonic	No music
Hits	0.700	0.665	0.726
	(0.189)	(0.188)	(0.175)
False alarms	0.035	0.092	0.031
	(0.063)	(0.145)	(0.049)

Response times

Figure 3 shows the mean RTs for all correct responses to Targets and Distractors in the Harmonic Music, Inharmonic Music, and No-Music conditions. While our goal was to primarily focus on the comparison between the Harmonic and Inharmonic Music conditions, we conducted the customary omnibus Analysis of Variance (ANOVA) examining three within-participant levels of Music (Harmonic, Inharmonic, and No music) and two within-participant levels of Trial Type (Distractor, Target). The ANOVA confirmed that there were main effects of Music, $F(1,47) = 10.751$, $p < 0.0001$ and Trial Type, $F(1,47) = 35.506$, $p < 0.0001$, but no interaction between these two factors, $F(1,47) = 0.714$, $p = 0.492$. We began our planned analyses of the RTs by focusing on the Harmonic Music and Inharmonic Music conditions, using an ANOVA with the within-participant factors of Music (Harmonic, Inharmonic) and Trial Type (Distractor, Target) to analyze the data. We found that RTs were slower (mean difference = 40 ms) in the Inharmonic Music condition than in the Harmonic Music condition, $F(1,47) = 7.028$, $p = 0.011$. Participants also responded more slowly (mean difference = 86 ms) on Target trials than on Distractor trials, $F(1,47) = 25.429$, $p < 0.0001$. The interaction between Music and Trial Type did not reach significance, $F(1,47) = 0.920$, $p = 0.342$.

For the sake of completeness, we next focused on comparing the Inharmonic Music and the No-Music conditions, submitting the mean RTs for each of these Music conditions (Inharmonic Music, No Music) as a within-participant factor to an ANOVA, which also included Trial Type (Distractor, Target) as a within-participant factor. RTs were slower in the Inharmonic Music condition than in the No-Music condition, $F(1,47) = 19.005$, $p < 0.0001$ (mean difference = 67 ms) and slower on Target trials than on Distractor trials, $F(1,47) = 36.977$, $p < 0.0001$ (mean difference = 85 ms). There was no statistically significant interaction between Music and Trial Type, $F(1,47) = 1.208$, $p = 0.277$.

To directly compare RTs in the Harmonic Music and No-Music conditions we again employed a repeated measures ANOVA assessing Music (Harmonic Music, No Music) and Trial Type (Distractor, Target). The main effect of Music was statistically significant, $F(1,47) = 4.256$, $p = 0.045$ (mean difference = 26 ms), with responses being slower in the Harmonic Music condition relative to the No-Music condition. The main effect of Trial Type was also significant, $F(1, 47) = 33.147$, $p < 0.0001$ (mean difference = 96 ms), with responses being slower on Target trials than on Distractor trials. The interaction between our two factors was not significant, $F(1,47) = 0.002$, $p = 0.967$.

Summary and discussion

Analyses of participants' phenomenological appraisals of the harmonic and inharmonic music confirmed that our inharmonic music was indeed experienced as being more unpleasant and dissonant than our harmonic music. Both the accuracy and the RT data showed that performance on the 2-back task was poorer when dissonant (inharmonic) music was played relative to when consonant (harmonic) music was played, suggesting that dissonant music poses greater interference with cognitive processing than does consonant music. These performance effects were observed even though participants

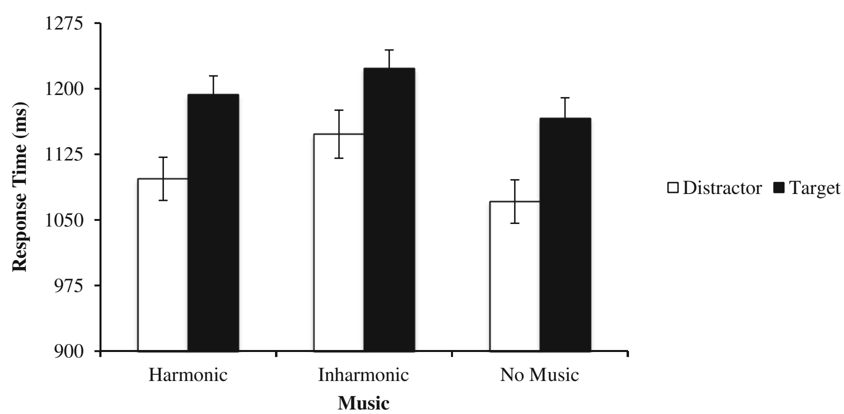

Fig. 3 Mean correct response times in milliseconds for each condition and trial type in Experiment 1 (n = 48). Error bars represent one standard error of the mean

were given explicit instructions to focus on the primary task and to respond as quickly and accurately as possible. This suggests that the cognitive processing demands of dissonant music are automatic to some extent and cannot be completely suppressed with strategic control. Poorer performance on the 2-back task was also observed when participants were presented with inharmonic music compared to when they were presented with no music. There were no detectable accuracy differences in performance on the 2-back task when participants were exposed to harmonic music compared to no music. However, responses were slightly slower in the Harmonic Music condition relative to the No-Music condition despite explicit instructions to ignore the music in the Harmonic Music condition. This finding is consistent with the irrelevant sound effect literature (e.g., Tremblay & Jones, 1998) in that it might reflect a small tendency for even harmonic music to disrupt performance relative to a situation in which no music is presented. We suggest that this slowing effect be treated with caution as it was relatively small, and was not found in our previous pilot study.

Experiment 2

Introduction

The main conclusion we have drawn from Experiment 1 is that inharmonic music not only results in negative affect typical of dissonance phenomenology, but also interferes with the performance of a concurrent cognitive task to a greater extent than does harmonic music (and also no music). However, in Experiment 1, the 2-back task and the distracting music were presented in the same sensory modality, which leaves open the possibility that the measured performance decrements could be attributed to low-level sensory interference rather than cognitive processing demands. To address this possibility, in Experiment 2 we presented the stimuli for the 2-back task and the distracting music in different modalities. Specifically, we presented participants with a *visual* 2-back task while presenting the harmonic or inharmonic music diotically. In doing so, we precluded any opportunity for sensory interference between the primary 2-back task and the distracting music.

In Experiment 2 we also modified the order of the presentation of the No-Music, Harmonic Music, and Inharmonic Music conditions. In the previous experiments, each of these conditions was tested in a separate block of trials with the blocks being fully counterbalanced across participants. A weakness of this design, however, is that variance associated with learning the 2-back task likely contaminates the responses in whichever condition is tested first, thus adding noise to the primary comparison of the Harmonic Music and Inharmonic Music conditions. To reduce this problem, we had each participant first complete the 2-back task in the absence of music. In other words, participants were given the No-Music condition first, followed by counterbalanced blocks of either harmonic or inharmonic music. We expected that variability imposed by learning would be absorbed in the first (No Music) block leaving less unwanted learning-related variance in the comparison between Harmonic Music and Inharmonic Music blocks. This of course meant that any comparisons with the No-Music condition were confounded by order effects (as the No-Music condition was always presented first), so we did not conduct statistical comparisons of the difference in performance between this condition and that in either the Harmonic Music or Inharmonic Music conditions. We felt this was no great loss, however, because our primary comparison of interest was between the Harmonic Music and the Inharmonic Music conditions, and our spectral manipulations served as the effective experimental control. In all other ways, Experiment 2 was the same as Experiment 1.

Method

Participants

The final analysis included 48 undergraduate students (mean age = 19.01 years, SD = 1.56 years; 13 male) from the University of Waterloo. Participants were granted partial course credit after completing the 30-min experiment. While we did not select participants based on their musical training, participants reported they received music lessons ranging from 1 to 18 years (mean = 5.00 years, SD = 3.88 years).

A sample size of 48 participants was predetermined for Experiment 2 before data collection began based on the results of Experiment 1. After completing data collection for an initial sample of 48 participants, the data from four participants were excluded from the original data set for behavioral non-compliance (three participants prematurely terminated the experiment, and one participant systematically responded “no, no, yes” for the duration of the experiment, irrespective of the targets in the to-be-attended stream). Data from two additional participants were excluded because their response accuracy fell 2.5 standard deviations below the mean. As a result, six additional participants were recruited to complete the full counterbalance and reach the predetermined sample size of 48.

Apparatus and stimuli

The apparatus and stimuli were identical to those used in Experiment 2 except that the numbers 1–9 of the 2-back task were presented in print (80 pt Helvetica font; height = 1.25 cm) in the center of the computer screen in white font against a black background. We did not constrain participants' head movements or the distance at which they were required to view the screen; however, participants were seated at a normal sitting distance from the screen. The randomization constraints of the 2-back task were identical to those used in Experiment 1. The distracting music stimuli were identical to those in Experiment 1, with the only difference being that the music was presented diotically (i.e., with the same signal to both ears).

Procedure

Each trial of the 2-back task began with the presentation of a white fixation cross for 500 ms in the middle of a full-screen with a black background. The fixation cross was then replaced by one of the numbers of the 2-back task for 500 ms. A black background persisted for 1,500 ms before the next trial began. Critically, while participants completed three blocks of trials as in Experiment 1, they always completed the No-Music condition first, followed by the counterbalanced presentation of the Harmonic Music and Inharmonic Music conditions.

Results

Phenomenological appraisals

As in Experiment 1, we conducted analyses of participants' phenomenological appraisals of the music. Mean phenomenological appraisals (i.e. "Pleasant," "Unpleasant," "Consonant, " and "Dissonant") for each of the harmonic and inharmonic musical pieces were submitted as the dependent variable to separate repeated measures two-tailed t-tests. The means of each rating are reported in Fig. 4.

Consistent with the previous experiment, the inharmonic music was rated as less "pleasant," $t(1,47) = 10.840$, $p < 0.0001$, more "unpleasant," $t(1,47) = 5.301$, $p < 0.0001$, less "consonant," $t(1,47) = 2.976$, $p = 0.005$, and more "dissonant," $t(1,20) = 2.702$, $p = 0.01$ than the harmonic music.

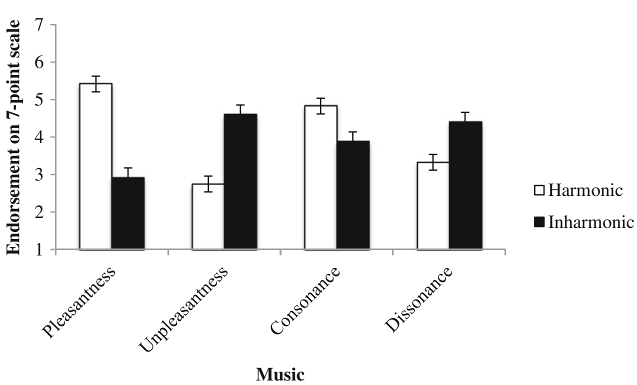

Fig. 4 Mean phenomenological appraisals of the harmonic and inharmonic music in Experiment 2 (n = 48). Larger numbers indicate greater experience of the rated dimension (1 = not at all, 7 = very). Error bars represent one standard error of the mean

Accuracy

The means of the hit rates and false alarm rates from the 2-back task for the Harmonic Music, Inharmonic Music, and No-Music conditions are presented in Table 2. Though we include the descriptive statistics from the No-Music condition for completeness, we focus only on comparing the A' scores between the Harmonic Music and Inharmonic Music conditions (shown in Fig. 5). Consistent with the findings in Experiment 1, analysis of the A' scores using a repeated-measures t-test showed that performance on the 2-back task was poorer in the Inharmonic Music condition than in the Harmonic Music condition, $t(1,47) = 2.835$, $p = 0.007$ (mean A' difference = 0.024).

Response times

The mean RTs for all correct responses to the 2-back task in each condition are reported in Fig. 6. We note that the RTs are much faster in this experiment than in Experiment 1. This is likely due in part because auditory stimuli must unfold over time, whereas visual stimuli are present instantaneously. Indeed, previous research has found faster RTs to visual stimuli than to auditory stimuli (e.g., Seli, Cheyne, Barton, & Smilek, 2012), and this is also true specifically in the 2-back task (Owen, McMillan, Laird, & Bullmore, 2005). Again, due to the fact that the No-Music condition was always presented first (and not counterbalanced with the other conditions), we focused only on comparing the Harmonic Music and Inharmonic Music conditions, but include data from the No-Music condition in the table for completeness. The mean RTs were assessed with a Music (Harmonic, Inharmonic) by Trial Type (Distractor, Target) repeated measures ANOVA. Most importantly, as in each of the previous studies, we found that responses on the 2-back task were slower in the Inharmonic Music condition than in the Harmonic Music condition, $F(1,47) = 32.316$, $p < 0.0001$ (mean difference = 61 ms). The analysis also revealed a main effect of Trial Type, $F(1,47) = 25.429$, $p < 0.0001$ (mean difference = 80 ms), indicating that responses were slower on Target trials than on Distractor

Table 2 Mean hit rates and false alarm rates (and standard deviations) for each condition in Experiment 2 (n = 48)

Accuracy index	Music		
	Harmonic	Inharmonic	No music (practice)
Hits	0.636	0.632	0.706
	(0.227)	(0.213)	(0.199)
False alarms	0.053	0.101	0.077
	(0.059)	(0.075)	(0.082)

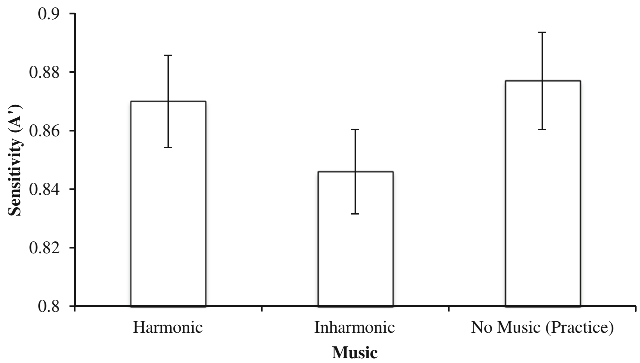

Fig. 5 Mean sensitivity (A') for each condition in Experiment 2 (n = 48). Error bars represent one standard error of the mean

trials. Interestingly, there was also a significant interaction between Music and Trial Type, $F(1,47) = 4.647$, $p = 0.036$, indicating that the longer RTs observed on Target trials relative to Distractor trials were more pronounced in the Inharmonic Music condition than in the Harmonic Music condition. As this interaction was not of primary interest, we did not pursue it with further analyses.

Summary and discussion

Consistent with Experiment 1, we found in Experiment 2 that performance on the primary cognitively demanding 2-back task was slower and less accurate when participants were exposed to inharmonic music than when they were exposed to harmonic music. Critically, we observed these results in a cross-modal paradigm that precluded any low-level sensory interference between the music and primary cognitive task. Our results strongly suggest that the dissonance elicited by inharmonic music is not only characterized by increased negative affect relative to consonant harmonic music, but that it also interferes with general cognitive performance to a greater extent than does consonant harmonic music.

General discussion

The primary goal of the present research was to evaluate the possibility that dissonant music interferes with cognitive performance to a greater extent than does consonant music. We reasoned that if these differential interference effects are potentially rooted in affect, arousal, or sensory complexity, then they should occur in the absence of any response selection conflict (cf., Masataka & Perlovsky, 2013) and might best be measured while participants are required to sustain cognitive processing of a difficult attentionally demanding task. In Experiment 1 we employed an auditory 2-back task as the primary cognitively demanding task. The stimuli for the primary 2-back task were presented in one ear and the distracting to-be-ignored music was presented in the other ear. Participants' phenomenological appraisals of our novel musical stimuli confirmed that the inharmonic music was experienced as "dissonant" and "unpleasant," while the harmonic music was experienced as "consonant" and "pleasant." Consistent with our hypothesis, performance on the 2-back task was worse under simultaneous exposure to dissonant inharmonic music compared to simultaneous exposure to consonant harmonic music. In Experiment 2, we again found that dissonant music produces greater cognitive interference than consonant music, even when the primary task was presented in the visual modality. This manipulation precluded any explanation of the interference effects in terms of low-level sensory interference between the primary task and the musical distractors. Interestingly, these interfering effects of inharmonic music seem to be due to spontaneous cognitive processing that eludes strategic control, as they arose despite repeated instructions to ignore the distracting music and to respond as quickly and accurately as possible to the primary 2-back task.

Our results extend previous findings in several ways. Our findings are consistent with those of Masataka and Perlovsky (2013), who found that dissonant music led to slower and less accurate responses to incongruent Stroop trials than did

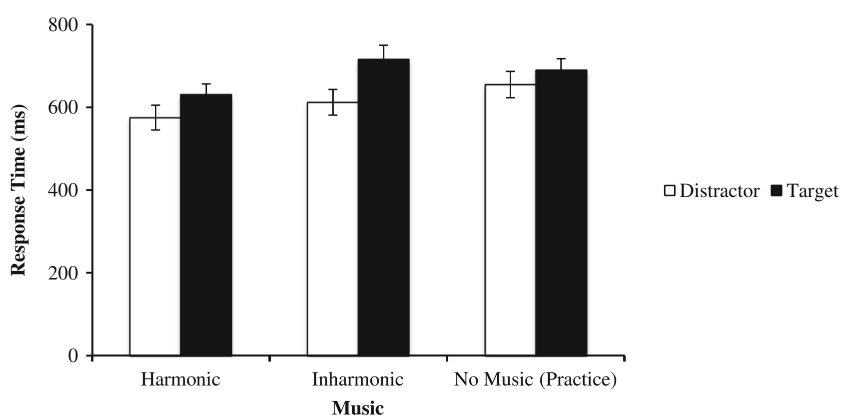

Fig. 6 Mean correct response times in milliseconds for each condition and trial type in Experiment 2 (n = 48). Error bars represent one standard error of the mean

consonant music. Unlike those of Masataka and Perlovsky (2013), however, our results indicate that the interfering effects of dissonant music relative to consonant music can occur during more general cognitive processes, and specifically without response selection conflicts in the primary task as suggested by those authors. Accordingly, our results extend and broaden the empirical evidence in support of the notion that dissonance interferes with general cognitive performance to a greater extent than consonant music. Furthermore, our results contrast with those of Bodner, Gilboa, and Amir (2007), who found that relative to consonant music, dissonant music improved performance on the cognitively demanding Letter Cancellation and Adjective Recall from a Story tasks. Importantly, our results are nevertheless consistent with Bodner et al.'s (2007) general theoretical framework focused on the concept of arousal. Applying the authors' arousal model, one potential explanation of our results is that our dissonant musical stimulus heightened participants' level of arousal beyond that which optimally facilitates cognitive performance, whereas our consonant musical stimulus elicited arousal levels that allowed for better task performance.

In the Introduction we noted several other reasons why one might broadly expect dissonant music to interfere with cognitive performance to a greater extent than consonant music. Given our findings and the methodological details of the present experiments, we can now discuss each of these possibilities further. While at this point we cannot adjudicate between these accounts, we can comment on their respective utilities. Although Bodner, Gilboa, and Amir's (2007) arousal account does sufficiently explain the behavioral performance in our present study, it lacks specificity of the cognitive mechanisms at play and does not make specific predictions about particular levels of arousal that might lead to interfering effects in a given task or situation. Thus, the arousal account is limited in both its explanatory specificity and its predictive capability. The negative affect account exhibits the same limitations, as it has been associated with both cognitive impairments and enhancements, and also lacks a clear mechanistic interface with cognitive processing. Another possible explanation noted in our Introduction was a potentially higher prevalence of "salient state changes" within dissonant music compared to consonant music (cf., Schlittmeier et al., 2012; Schlittmeier, Hellbrück & Klatte, 2008). While this account might explain the interfering effects of some dissonant musical stimuli, specifically those containing salient, sporadic inharmonic intervals, it is perhaps less useful in explaining the results reported here. This is because our dissonant stimulus was comprised almost entirely of inharmonic intervals, resulting in a perception of dissonance that was sustained throughout the entire composition and precluding any given dissonant moment from being experienced as particularly salient. Thus, as the consonant stimulus used here was sparse in its salient state changes as a result of its uniform harmonicity, so too might its dissonant counterpart be considered sparse in its salient state changes as a result of its uniform inharmonicity.

Perhaps the most empirically tenable framework going forward is one that makes predictions about the differential cognitive demands that might be imposed by dissonant and consonant music. We suggest that inharmonic music might interfere with cognitive performance to a greater extent than harmonic music because its particular milieu of psychophysical properties requires greater cognitive processing than that of harmonic music. Specifically, we suggest that the cognitive responses to inharmonic music indicate an underlying conflict in auditory perception that is not presented by harmonic music. To nest our discussion within the pre-existing literature we will relate the following speculation to the well-established principles of auditory scene analysis (ASA; Bregman, 1990). ASA describes a series of parametric analyses conducted on incoming auditory stimulation by the brain. The primary function of these analyses is to form a veridical percept of the physical world. As in visual perception, the output of a given analysis consists of an interpretation about the number and types of objects in the surrounding environment (Bregman, 1990). Together, these analyses produce *streams* of the sounding objects that belong together in auditory perception.

One of these analyses concerns the harmonicity of the stimulus: harmonic frequency content will coalesce (fuse) within a single stream of the auditory percept, biasing the interpretation towards a single unified sound source. In contrast, inharmonic stimulation will diverge (segregate) into different streams within the percept, producing an interpretation of multiple, disparate sound sources (e.g., Moore, Glasberg, & Peters, 1986). Another analysis concerns the incident location of the stimulus: frequency content originating from a unified location will fuse within the percept as a single stream while frequency content originating from disparate spatial locations will segregate into independent streams of a multi-source percept (e.g., Cusack, Decks, Aikman, & Carlyon, 2004). The same is true of the onset and offset envelopes of various frequency components: those frequencies with simultaneous temporal onsets and offsets will be fused in perception while those of temporally displaced envelopes will be segregated in perception (e.g., Chalikia & Bregman, 1989). Lastly, timbral analysis produces strong streaming biases: stable (unchanging) timbres fuse within perception and deviant (changing) timbres are segregated in perception (e.g., Culling & Darwin, 1993).

In most auditory environments, the perceptual bias derived from one stimulus parameter is compatible with that of the other parameters. For example, inharmonic stimuli generally arise from disparate spatial locations with asynchronous onset and offset envelopes and deviant or changing timbres. Indeed, the brain is quite adept at parsing complex acoustic environments into multi-source percepts, so it is unlikely that such a common, essential procedure should produce the cognitive loads the listener experiences when exposed to inharmonic, dissonant music. Instead, we suggest that dissonant music produces a particularly auditory scene that the brain is ill-equipped to interpret. We can gain insight into this peculiarity by considering the acoustic inharmonicity of dissonant music with respect to the music's other acoustic parameters. In contrast to the usual coincidence of inharmonicity with disparate spatial locations, asynchronous temporal information, and deviant timbres, the inharmonicity of dissonant music is accompanied by unified spatial location, simultaneous event onsets and offsets (on the level of notes, rhythms, and beats), and a uniform timbre—all indicative of an alternative, single sound source interpretation. Now the brain is left with a perceptual dilemma: is the incoming stimulation coming from one unified sound source, or multiple sound sources? And if it is indeed multiple sources, how many are there, and why do they seem so coincident on so many dimensions? It is this incompatibility between the inferences derived from multiple ASA parameters that might underlie the cognitive resource demands of inharmonic music. Multiple simultaneous but incompatible inferences about the physical environment should naturally be expected to garner significant cognitive processing, even at an expense to performance in concurrent primary tasks.

One advantage of the foregoing account is that it provides a deeper understanding of how the acoustic complexity of inharmonic music might influence performance on concurrent tasks while remaining consistent with research that emphasizes the influence of prior musical experience (i.e., expertise) on consonance and dissonance appraisals. Our account leaves room for the role of musical experience because prior experience and expertise with a class of stimuli is known to reduce the amount of cognitive resources required to process the stimuli (Wiesmann & Ishai, 2011). Accordingly, one might expect that prior experience and expertise with inharmonic music might reduce the cognitive resource demands imposed by inharmonic stimuli. Indeed, inharmonicity is embraced as an essential component of the preferred musical aesthetic by listeners of many non-Western (Vassilakis, 2005) and tonally complex Western genres (e.g., jazz; Dibben, 1999) where such tonalities are prevalent. Similarly, this account also leaves room for the possibility that, under specific conditions, *harmonic* music might interfere with performance of ongoing tasks. For instance, locally harmonic chords (e.g., major chords) are experienced as dissonant when they interrupt musical passages of a separate key (Bigand, Parncutt, & Lerdahl, 1996). In doing so, they violate the listener's expectations of the musical passage produced by the prevalent tonality of the auditory percept. According to our account, this violation is akin to that introduced by locally inharmonic chords, in that the locally harmonic chord contains frequency content that is incompatible with the global musical passage (auditory stream) and generates an unstable auditory percept, which in turn leads to greater processing demands. Work by McLachlan, Marco, Light, and Wilson (2013) corroborates this interpretation, arguing that dissonance arises from the cognitive incongruity between perceived and expected (long-term memory) templates of common chords.

Lastly, this interpretation is readily compatible with research conducted on the irrelevant sound effect. Of particular relevance is the finding by Jones, Alford, Bridges, and Macken (1999) that irrelevant sounds with segregated inharmonic components are less distracting than those with fused inharmonic components. The authors found that distractors containing tones deviant in both pitch and timbre were less distracting than those containing tones that deviated in either pitch or timbre. Furthermore, the authors found that the former stimuli were no more distracting than a monotonous distractor that did not contain any tone deviants (Jones et al., 1999). Interpreting their results, the authors suggested, "Perhaps the key to understanding these contrary effects lies in an understanding of the modulating influence of auditory stream formation and its consequences for seriation," (i.e., the encoding of a particular auditory stream), concluding in essence that when a tone is deviant in two parameters it is most easily streamed as a separate auditory object that does not interfere with the seriation of either the primary or distracting events. Consistent with our discussion, then, is the conclusion that the heightened distractibility of dissonant music relative to consonant music may be related to a perceptual dilemma instantiated by the unlikely but tenacious fusion of inharmonic frequency components within a single auditory stream.

Conclusion

While the available data do not allow us to precisely elucidate all of the links among acoustic harmonicity, cognitive resource demands, and consonance-dissonance, the present findings provide an important piece to the puzzle. We provide novel evidence that dissonant music interferes with cognitive performance to a greater extent than consonant music on a generally demanding cognitive task that does not entail response selection conflict. This evidence strongly suggests that dissonant music produces a general cognitive interference which is greater than that produced by consonant music. Lastly, in interpreting our results we described a potential mechanism rooted in the principles of auditory scene analysis that we believe generates testable predictions about listeners' differential cognitive responses to consonant and dissonant music that could inspire future empirical research.

Author note This research was supported by a Natural Sciences and Engineering Research Council of Canada (NSERC) discovery grant to DS.

The authors convey their appreciation for the data collection contributions of our research assistants Tracy Duncan, Jennifer Chandrabose, Laura Obdeyn, and Katherine Patricia Paus, without whom this project could not have materialized in such a timely fashion.

Appendix

Table 3 I. Pitch ranges for each contrapuntal voice and the pitch substitutions between harmonic and inharmonic pieces

Voice	Frequency range	Pitch substitutions	
		Harmonic	Inharmonic
1	F0 – A2	C1	C#1
		F1	F#1
2	E1 – C3	E2	Eb2
		A3	Ab3
3	F2 – G4	A3	Ab3
		C3	C#3
		E3	Eb3
		C4	C#4
		E4	Eb4
		G4	Gb4
4	C3 – G5	F3	F#3
		G3	G#3
5	C4 – F5	C4	C#4
		E4	Eb4
		A5	Ab5
		B5	Bb5
		C5	C#5
6	G4 – E6	No substitutions	

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