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Shared structural and temporal integration resources for music and arithmetic processing

L. Hoch *, B. Tillmann

CNRS, UMR5292, INSERM, U1028, Lyon Neuroscience Research Center, Auditory Cognition and Psychoacoustics Team, Lyon, F-69000, France
University Lyon, F-69000, France
University Lyon 1, Villeurbanne, F-69000, France

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While previous research has investigated the relationship either between language and music processing or between language and arithmetic processing, the present study investigated the relationship between music and arithmetic processing. Rule-governed number series, with the final number being a correct or incorrect series ending, were visually presented in synchrony with musical sequences, with the final chord functioning as the expected tonic or the less-expected subdominant chord (i.e., tonal function manipulation). Participants were asked to judge the correctness of the final number as quickly and accurately as possible. The results revealed an interaction between the processing of series ending and the processing of the task-irrelevant chords' tonal function, thus suggesting that music and arithmetic processing share cognitive resources. These findings are discussed in terms of general temporal and structural integration resources for linguistic and non-linguistic rule-governed sequences.

1. Introduction

Psycholinguistic research has inspired music cognition research and together, they have provided new insights in the comprehension of brain functions, notably by suggesting shared structural and temporal integration resources for language and music processing (e.g., Patel, 2008). It has been suggested that the investigation of structured material processing needs now to go beyond language and music domains (e.g., Jackendoff, 2009). Our study thus investigated the relationship between music and arithmetic processing, by using a cross-modal paradigm previously used to investigate the simultaneous processing of music and language (Hoch, Poulin-Charronnat, & Tillmann, 2011).

Language and music are combinatorial systems that are structurally organized by syntactic rules of which listeners have implicit knowledge (Jackendoff, 2009; Patel, 2008). These rules allow combining basic elements (e.g., phonemes, tones) into units (e.g., words, chords) that can be combined into larger units (i.e., sentences, musical sequences). In language, knowledge about syntactic structures (e.g., word order, gender agreement) allows developing syntactic expectations about future events that influence, for example, word processing (e.g., Blumstein, Milberg, Dworetzky, Rosen, & Gershberg, 1991; Gibson, 1998; Levy, 2008). In the music domain, musical syntax defines hierarchically organized tonal functions that depend on the installed tonal context (e.g., Krumhansl, 1990; Tillmann, Janata, Birk, & Bharucha, 2003, 2008). For example, a C-major chord (consisting of the tones C, E and G) functions as a tonic chord, the most important chord in the context of the C-major key. In contrast, the same chord functions as a less-important subdominant chord in the context of the G-major key, and as an out-of key chord (i.e., being a strong music-syntactic violation) in the context of the D-major key. Western listeners have acquired implicit knowledge about musical structures and tonal functions that allow developing tonal expectations for future musical events: The musical priming paradigm has shown facilitated processing of structurally related (and thus supposed to be expected) events (i.e., faster processing for the expected tonic than for the less-expected subdominant, see Tillmann, 2005 for a review).

Structural similarities for language and music together with parallel data patterns observed for language and music processing have led Patel (2003) to develop the Shared Syntactic Integration Resources Hypothesis (SSIRH) that proposes shared resources for structural integration of events over time in language and music. Notably, neurophysiological studies have reported activations in the inferior frontal gyrus (IFG) with a left-hemisphere dominance for linguistic structure processing (Friederici, Ruschemeyer, Hahne, & Fiebach, 2003; Hagoort, 2005) and a right-hemisphere dominance for musical structure processing (Koelsch et al., 2002; Levitin & Menon, 2003; Maess, Koelsch,

* Corresponding author at: Lyon Neuroscience Research Center, Team Auditory Cognition and Psychoacoustics, 50 Av. Tony Garnier, F-69366 Lyon Cedex 07, France. Tel.: +33 4 37 28 74 90; fax: +33 4 37 28 76 01.
E-mail address: Lisianne.Hoch@olfac.univ-lyon1.fr (L. Hoch).

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Gunter, & Friederici, 2001; Tillmann, Janata, & Bharucha, 2003; Tillmann et al., 2006). In addition, syntactic processing in language and music elicited similar ERPs, notably a posterior positivity around 600 ms (i.e., P600) that was modulated by the difficulty to integrate the syntactic violation in the context, in both domains (Patel, Gibson, Ratner, Besson, & Holcomb, 1998). This P600 has been interpreted as reflecting a non-specific electrophysiological marker of structural integration. The SSIRH has then encouraged new research on simultaneous language and music processing that reported interactive influences between syntactic processing in language and music (e.g., Fedorenko, Patel, Casasanto, Winawer, & Gibson, 2009; Hoch et al., 2011; Koelsch, Gunter, Wittfoth, & Sammler, 2005; Slevc, Rosenberg, & Patel, 2009; Steinbeis & Koelsch, 2008).

Next to language and music, arithmetic is also a combinatorial system that is structurally organized by rules and that requires knowledge-based structural integration of events into a mental representation (Friedrich & Friederici, 2009). The rules allow combining quantities to produce new quantities: For example, the summation of the quantities *2* and *4* equals *6* (i.e., $4+2=6$). Individuals have knowledge about arithmetic rules that allow developing arithmetic expectations as suggested by faster verification for correct resultants (e.g., $3\times8=24$) than for incorrect resultants (e.g., $3\times8=48$; Niedeggen & Rösler, 1999; Niedeggen, Rösler, & Jost, 1999).

The influence of arithmetic expectations on number processing has also been shown in ERP studies reporting a P600 for the processing of incorrect arithmetic series ending (Núñez-Peña, Cortinas, & Escera, 2006; Núñez-Peña & Escera, 2007; Núñez-Peña & Honrubia-Serrano, 2004; Núñez-Peña, Honrubia-Serrano, & Escera, 2005). In addition, this P600 was modulated by the integration difficulty of the series endings (Núñez-Peña & Escera, 2007; Núñez-Peña & Honrubia-Serrano, 2004; see also Niedeggen & Rösler, 1999). The P600 has been shown to be similar for the processing of arithmetic and linguistic–syntactic violations (Martín-Loeches, Casado, Gonzalo, De Heras, & Fernández-Frías, 2006), thus suggesting shared structural and temporal integration resources for arithmetic and language processing. This hypothesis has received further support from 1) neurophysiological studies reporting left IFG activation for arithmetic processing, thus partially overlapping with linguistic structure processing (Baldo & Dronkers, 2007; see also Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Friedrich & Friederici, 2009; Kong et al., 2005; Menon, Mackenzie, Rivera, & Reiss, 2002; Rickard et al., 2000), and 2) a behavioral study reporting interactive influences between simultaneous arithmetic and linguistic–syntactic processing (Fedorenko, Gibson, & Rohde, 2007).

While some authors underline the overlap between arithmetic and linguistic processing, also based on data obtained with patients showing deficits in both domains (e.g., Dehaene & Cohen, 1997), others underline that, despite structural analogies, mathematics and language are processed differently and more independently, as also based on patients showing functional dissociations between the two domains (e.g., Friedrich & Friederici, 2009; Gelman & Butterworth, 2005; Varley, Klessinger, Romanowski, & Siegal, 2005).

In sum, previous studies have investigated either language and music structure processing or language and arithmetic structure processing. The question thus raises whether the previous findings predict also shared resources for music and arithmetic processing or whether one might rather argue that even though similar neural networks might be involved, it remains to be shown that the partial overlap between arithmetic and language also concerns music processing. Up to now, only one study has investigated music and mathematics in the same participants, albeit with separate tasks and focussing on spatial processing. Interestingly, their findings provide little evidence for shared spatial representation processes and performance in musical and mathematical tasks, which appeared to be largely independent (Beecham, Reeve, & Wilson, 2009).

Our study investigated the hypothesis of shared resources between simultaneous music and arithmetic structure processing. For this aim, we used a cross-modal paradigm as previously used for the investigation of interactive influences between simultaneous music and language processing (Hoch et al., 2011; see also Koelsch et al., 2005; Slevc et al., 2009; Steinbeis & Koelsch, 2008). Series of eight Arabic numbers (e.g., Núñez-Peña & Honrubia-Serrano, 2004) were visually displayed in synchrony with musical sequences of eight chords. For the musical sequences, the tonal function of the task-irrelevant final chord was manipulated so that the final chord functioned as an expected tonic chord or a less-expected subdominant chord. For the arithmetic series, the final number defined the target, which was either a correct or incorrect series ending according to the arithmetic rule developped by the preceding context. Participants were asked to verify the correctness of the target as accurately and quickly as possible. Four arithmetic rules (i.e., $+2$, $+4$, -2 and -4) were used to increase variability in the experimental materials, and thus to encourage participants to remain focused on the entire series for each trial. Additionally, this variability in the arithmetic materials allowed investigating a potential influence of the integration difficulty, notably as a function of the rules developed in the context (e.g., small *versus* large increments, previously referred to as the problem size effect; Ashcraft, 1992; Ashcraft & Battaglia, 1978; LeFevre, Sadesky, & Bisanz, 1996; Núñez-Peña et al., 2006). Hence, this manipulation also allowed us to go further than the previous studies investigating the interaction between language and music with only one complexity level of syntactic (linguistic) structures in the same participants.

Performance in the verification task should be more accurate and faster for correct than incorrect series endings, as the correct ending is supposed to match participants' expectations while the incorrect ending does not (e.g., see Niedeggen & Rösler, 1999). If music and arithmetic processing share structural integration resources, as suggested by previous research in each domain, respectively, we should observe an interaction between series ending (correct, incorrect) and the tonal function of the final chord (tonic and subdominant chords, which were expected and less expected, respectively). Interactive effects between arithmetic and music processing should be particularly pronounced for the large problem-size series, which were supposed to be more difficult to integrate. Based on the previously reported benefit of the tonic (without cost for the subdominant, in comparison to a baseline condition) in a cross-modal paradigm (Escoffier & Tillmann, 2008),[1] we expected interference between the two structures to be reflected in an overall reduced (or vanished) tonic facilitation. In addition, incorrect series ending verification might be slower when presented with the less-expected chord than with the expected chord, as suggested by previous data on complex syntax manipulation with increased integration demands (syntactic garden-path sentences presented with musical sequences in a cross-modal paradigm, Slevc et al., 2009).

2. Method

2.1. Participants

Thirty-six students (28 females) from the University of Lyon participated in the experiment. One female participant was removed from the analyses because of slower average RTs than the group

[1] In the study by Escoffier and Tillmann (2008), cross-modal influences were tested not only with the musical sequences ending on tonic and subdominant chords, but also with (neutral) baseline sequences, which did not install a tonal center and thus did not allow for developing tonal expectations for the final chord. This study showed that (a) the RTs in the tonic condition were faster than in the baseline condition, thus suggesting a facilitation for the tonic chord, and (b) the RTs did not differ between the subdominant condition (i.e., with the potential deviant) and the baseline condition. This finding suggests that the cross-modal influences are unlikely to be due to auditory deviance detection mechanisms shifting attention away from the visual target (because of the less-related subdominant chord). If the cross-modal effect were caused by a disruption of visual processing due to an attentional shift to the less-expected subdominant chord, RTs would have been expected to be slower in the subdominant condition than in the baseline condition.

(i.e., +2 *SD*). For the 35 remaining participants, the mean age (±*SD*) was 20.56 years (±2.03). Number of years of formal musical training (measured with a questionnaire) ranged from 0 to 12 with a mean of 2.49 ($SD=3.65$) and a median of 0. Participants declared to have normal hearing.

2.2. Materials

2.2.1. Musical sequences

Twelve eight-chord piano sequences covering the twelve major keys were used (Bigand, Tillmann, Poulin, D'Adamo, & Madurell, 2001). For each musical sequence, the first seven chords defined the context and the eighth chord defined the final chord, which was either a tonic or a subdominant chord, resulting in 24 musical sequences. Each chord of the context sounded for 625 ms and the target chord sounded for 850 ms (with resonance). The inter-chord interval was null.

2.2.2. Number series

The number series were inspired by the work of Núñez-Peña and colleagues (e.g., Núñez-Peña & Honrubia-Serrano, 2004). A number series consisted of eight even[2] Arabic numbers (selected from a set ranging from 10 to 98) and was governed by one of four arithmetic rules. For each number series, the first seven numbers defined the context and the eighth number defined the target. Twenty-four series were generated from the following equation: $x_{i+1}=x_i+c$, where $i\in[1, 7]$ and c was a constant among [+2, +4, −2, −4]. For each constant, six series with different starting points were generated, thus providing 24 different number series. Twelve series were characterized by an increment size of *2* and 12 by an increment size of *4* (defining the problem size that was small or large, respectively). Among these 12 series with an increment size of *2* (and 12 series with an increment size of *4*), six were increasing series and six were decreasing series (defining the series direction). For each of the 24 series, the target number was either correct or incorrect according to the arithmetic rule developed in the preceding context (i.e., leading to 48 series). To encourage participants to perform exact calculations based on the underlying arithmetic rule rather than approximate calculations (El Yagoubi, Lemaire, & Besson, 2003; Menon et al., 2002; Núñez-Peña & Escera, 2007), the incorrect ending was a small deviation from the correct ending by adding 2 to the correct ending for increasing series (e.g., 12–14–16–18–20–22–24–*28*) and by subtracting 2 from the correct ending for decreasing series (e.g., 42–40–38–36–34–32–30–*26*). This allowed using the same numbers as both correct and incorrect series endings.

Each number was displayed on the centre of the screen. Each number of the context was presented in white on a black background during 380 ms (with an inter-stimulus interval of 245 ms as in Escoffier & Tillmann, 2008) and the target number was presented in red up to participants' response with a timeout of 1500 ms (as in Niedeggen et al., 1999).

2.2.3. Audio–visual presentation

The onset of each number was synchronized with the onset of each chord. The 48 number series were presented in synchrony with the musical sequences ending on either a tonic or a subdominant chord. The resulting 96 trials were presented in a pseudorandom order, so that the repetition of a given arithmetic or musical context and a given target number was not consecutive, but was separated by, at least, three other number series or musical contexts. In addition, no more than four successive trials displayed series with a correct (or incorrect) ending, small (or large) problems, increasing (or decreasing) series, nor a musical sequence ending on a tonic (or subdominant) chord.

2.2.4. Apparatus

Musical sequences were generated with Cubase 5.1 (Steinberg) and GrandPiano sound samples using Halion software sampler (Steinberg). The experiment was run with Psyscope Software (Cohen, MacWhinney, Flatt, & Provost, 1993).

2.3. Procedure

The experimental session started with four practice trials without musical background (series with two correct and two incorrect endings) and four practice trials with musical background (two correct and incorrect endings with musical sequences that ended either on the tonic or subdominant). Participants were asked to judge as accurately and quickly as possible whether the target number was correct or incorrect according to the preceding context by pressing one of two response keys. Error feedback was given for practice and experimental trials. Participants were informed that the second set of practice trial and the experimental trials were presented with a musical background, but that their task only concerned the visually displayed number series. Before the display of the first number, a fixation cross was displayed on the centre of the screen. A 250 ms noise mask followed each trial. A break of 15 s was given every 24 trials, and participants could take additional short breaks between trials. The entire testing session lasted about 30 min.

3. Results

Mean accuracy was 90.77%. Because of the range in average correct response times (RTs) between participants (from 434 ms to 1028 ms), RTs were individually normalized with a mean of 0 and a standard deviation of 1, providing z-scores. Percentages of correct responses and z-scores were analyzed by two 2×2 (Tonal Function [tonic, subdominant]×Series Ending [correct, incorrect]) ANOVAs.

For percentages of correct responses, the main effect of series ending tended to be significant, $F(1, 34)=3.81$, $p=.06$, $MSE=0.01$, indicating more accurate processing for correct (92%) than for incorrect (90%) endings. No other effects were significant ($p>.31$).

For normalized RTs (i.e., z-scores), the main effect of series ending was significant, $F(1, 34)=83.17$, $p<.001$, $MSE=.06$, indicating faster processing for correct endings than for incorrect endings. The main effect of tonal function was significant, $F(1, 34)=10.75$, $p<.005$, $MSE=.03$, and interacted with series ending, $F(1, 34)=3.95$, $p=.05$, $MSE=.07$ (Fig. 1): Arithmetic processing was significantly slower when presented with a subdominant rather than a tonic chord only for incorrect endings, $F(1, 34)=11.54$, $p<.005$, $MSE=.05$, but not for correct endings ($p=.89$).

To adress the potential contribution of musical expertise on the observed influence of musical structures, we selected the 16 participants who reported musical training (ranging from 1 to 12 years, $M=6.19$, $SD=3.49$, $Mdn=5.5$). Coefficients of correlation between the degree of musical training and the RT difference between tonic and subdominant chords for both correct endings ($r(14)=.18$, $p=.51$) and incorrect endings ($r(14)=.08$, $p=.77$) were not significant. This finding is in agreement with previous data sets that reported that the size of the observed musical priming effect was not correlated with years of musical training (e.g., Bharucha & Stoeckig, 1986; Tillmann & Bharucha, 2002), thus confirming that the musical structure processing is based on cognitive processes that do not require explicit musical knowledge.

To investigate potential influences of problem size and/or series direction, two supplementary analyses that included problem size (small, large) and series direction (increasing, decreasing) as additional within-participants factors were performed on accuracy and normalized response times (i.e., z-scores).

For percentages of correct responses, the additional analysis confirmed the marginally significant effect of series ending, $F(1, 34)=$

[2] In the present study, the number series only used even numbers to avoid that the correctness judgment was based on a parity-check strategy (see Núñez-Peña & Escera, 2007).

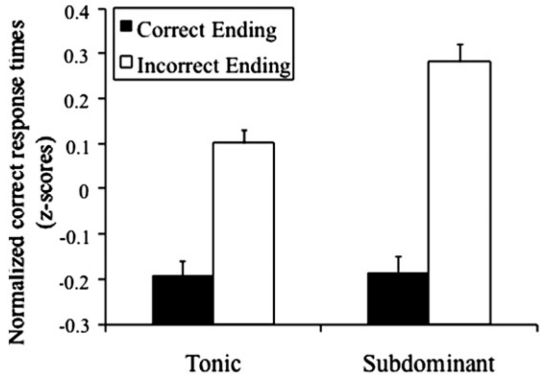

Fig. 1. Normalized response times (i.e., z-scores) presented as a function of series endings (correct, incorrect) and tonal function (tonic, subdominant). Errors bars indicate between-participants standard errors.

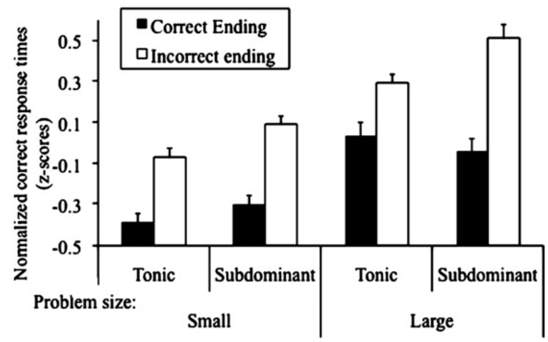

Fig. 2. Normalized response times (i.e., z-scores) presented as a function of series endings (correct, incorrect), tonal function (tonic, subdominant) and problem size (small, large). Errors bars indicate between-participants standard errors.

3.81, $p=.06$, $MSE=0.02$. In addition, the main effect of problem size was significant, $F(1, 34)=33.02$, $p<.001$, $MSE=0.03$: Verification was more accurate for small than for large problems. The significant effect of series direction, $F(1, 34)=18.03$, $p<.001$, $MSE=0.01$, interacted with problem size, $F(1, 34)=5.84$, $p<.05$, $MSE=0.01$: The better performance for small than large problems was more pronounced for decreasing series, $F(1, 34)=29.12$, $p<.001$, $MSE=0.03$, than increasing series, $F(1, 34)=12.65$, $p<.005$, $MSE=0.02$ (Table 1).

For normalized RTs (i.e., z-scores), the additional analysis confirmed the main effects of series ending, $F(1, 34)=75.65$, $p<.001$, $MSE=0.26$, and tonal function, $F(1, 34)=11.17$, $p<.005$, $MSE=0.12$, as well as the interaction between series ending and tonal function, $F(1, 34)=4.32$, $p<.05$, $MSE=0.27$.

In addition, the main effects of problem size and series direction were significant, $F(1, 34)=53.38$, $p<.001$, $MSE=.35$, $F(1, 34)=44.36$, $p<.001$, $MSE=.29$, indicating faster verification for small than large problems, and for increasing than decreasing series. As for percent of correct responses, the two-way interaction between problem size and series direction was significant, $F(1, 34)=8.10$, $p<.01$, $MSE=.18$: The effect of problem size was more pronounced for decreasing series, $F(1, 34)=45.55$, $p<.001$, $MSE=.34$, than for increasing series, $F(1, 34)=24.56$, $p<.001$, $MSE=.20$ (Table 1).

Most importantly, the two-way interaction between series ending and tonal function (as observed in the main analysis) was significantly modulated by the problem size, $F(1, 34)=4.74$, $p<.05$, $MSE=0.09$ (Fig. 2): The Tonal Function × Series Ending interaction was observed only for large problems, $F(1,34)=6.07$, $p<.05$, $MSE=0.25$, but not for small problems ($p=.36$). For small problems, a main effect of tonal function was observed, $F(1, 34)=10.07$, $p<.005$, $MSE=0.11$, indicating faster verification when the simultaneously presented musical sequence ended on a tonic than when it ended on a subdominant, independently of series ending.

Finally, tonal function also interacted with series direction, $F(1, 34)=4.70$, $p<.05$, $MSE=.19$: The tonal function effect (i.e., faster arithmetic processing for the tonic rather than the subdominant) was significant only for increasing series (30.84 ms), $F(1, 34)=13.82$, $p<.001$, $MSE=.16$, but not for decreasing series (5.22 ms, $p=.70$). However, this two-way interaction was not modulated by series ending ($p=.13$), and thus does not inform us about the influence of musical structure processing on the processing of arithmetic expectancy violations (i.e., correct versus incorrect ending). Based on the observed main effect of series direction (for correct responses and normalized RTs), the interaction between tonal function and series direction may rather reflect the influence of musical structure processing on the overall difficulty of arithmetic processing.

Table 1
Percent correct responses and normalized response times (i.e., z-scores) for the observed interaction between problem size (small, large) and series direction (increasing, decreasing). Between-participants standard errors were indicated in parenthesis.

Problem size	Series direction			
	Increasing series		Decreasing series	
	Small	Large	Small	Large
Percent correct responses	95.48 (0.01)	90.24 (0.01)	93.81 (0.01)	83.57 (0.02)
Z-scores	−0.27 (0.03)	−0.003 (0.04)	−0.07 (0.04)	0.40 (0.05)

4. Discussion

The present study investigated whether interactions can be observed for simultaneous music and arithmetic structure processing, as previously observed for simultaneous music and language structure processing. For this aim, we manipulated the tonal function of chords together with the ending of visually presented rule-based arithmetic series. Participants were asked to judge the correctness of the series ending while task-irrelevant chord sequences were presented as musical background. Our main finding was the observation of interactive influences between the simultaneous music and arithmetic structure processing, which were modulated by the degree of integration difficulty (as reflected in the three-way interaction between series ending, tonal function and problem size). Our results provide further insights about the influence of integration difficulty on interactive patterns between music and arithmetic processing, which also sheds new light on interactive patterns between music and language procesing. In particular, they encourage future music–language studies to manipulate levels of structural and temporal integration difficulty to further our understanding of the nature of shared cognitive resources.

Regarding our verification task of rule-governed number series ending, it is worth noting that participants were more accurate and faster for correct ending verification than for incorrect ending verification. Together with the overall accuracy, this series ending effect suggests that the arithmetic rule developed in the context has been discovered by the participants and allowed them to develop expectations about the series ending. Similar series ending effects have been reported for simple addition problems (Ashcraft & Battaglia, 1978; Szucs & Csépe, 2004) and multiplication problems (Niedeggen & Rösler, 1999; Niedeggen et al., 1999).

Most importantly, our present study showed interactive influences between (task-irrelevant) tonal function and (task-relevant) arithmetic processing. Previous studies investigating simultaneous music and language syntactic processing revealed interactive effects in cross-modal paradigms (Hoch et al., 2011; Slevc et al., 2009; see Koelsch et al., 2005; Steinbeis & Koelsch, 2008, for ERP studies) and in a self-paced listening task with sung music (Fedorenko et al., 2009). These interactions have been interpreted as reflecting shared structural integration resources. Similarly, the interactive pattern between music and arithmetic processing observed here may reflect shared structural and temporal integration resources, which are required to integrate an incoming (musical or arithmetic) event on the basis of the preceding events into a coherent (musical or arithmetic) structured representation.

The observation of interactive influences between music and arithmetic processing for large problems (i.e., increment size of 4), but not for small problems (i.e., increment size of 2) suggests that arithmetic processing is modulated by the difficulty of the simultaneous arithmetic task, and notably by the required structural and temporal integration of the arithmetic events. Indeed, we observed less accurate and slower verification performance for large problems than for small problems, as previously observed and referred to as the problem size effect (Ashcraft, 1992; Ashcraft & Battaglia, 1978; LeFevre et al., 1996; Núñez-Peña et al., 2006). The problem size effect has been interpreted as reflecting non-retrieval and highly demanding computational processes for large problem processing, while small problem processing relies on direct retrieval processes, which require less (or no) integration resources (LeFevre et al., 1996). The observation of an interaction between tonal function and series endings only for large problems, but not for small problems thus supports our interpretation in terms of shared structural and temporal integration resources. Small problems showed a main effect of tonal function as previously observed for sung and spoken syllables (Bigand et al., 2001; Hoch & Tillmann, 2010) as well as for visual syllables and geometric forms (Escoffier & Tillmann, 2008). The tonal function effect for geometric forms has been interpreted in terms of musical structure processing and dynamic attending mechanisms: Musical structures guide listeners' attention over time (Jones & Boltz, 1989), so that the tonic—functioning as an expected tonal accent—is related to increased attentional resources, which then benefit the simultaneous processing of other materials (e.g., syllables, geometric forms, numbers; see Escoffier & Tillmann, 2008).

In contrast, large problems showed an interaction between music and arithmetic processing. This interactive pattern suggests increased structural integration difficulty for large (over small) arithmetic problems, notably during the context *and* when both arithmetic and musical expectations were violated (i.e., incorrect series endings presented with the less-expected subdominant). For correct series endings of large problems, the missing tonic facilitation can be compared to the missing tonic facilitation observed for syntactically unexpected words in simple active sentences (Hoch et al., 2011, Experiment 1). In both situations, the increased level of integration difficulty led to a vanished tonic facilitation without an additional subdominant cost. For incorrect series endings of large problems, the vanished tonic facilitation seemed to be accompanied by a slowed-down processing due to the less-expected subdominant chord. This might be compared to the slowed-down processing of syntactic garden-path sentences when presented with an unexpected chord (Slevc et al., 2009). These comparisons suggest that for large problems, the incorrect series ending might require more integration resources than the correct series ending, as the syntactic complexity of the garden-path sentences (Slevc et al., 2009) would require more integration resources than an unexpected word in simple active sentences (Hoch et al., 2011). To further define the contributions underlying these interactive effects, future studies should systematically manipulate the complexity of the lingustic structures (or arithmetic sequences) and the strength of the musical structure violatons. These structural manipulations might then be further compared with neutral baseline conditions (for both tested materials).

In sum, the present study investigated simultaneous processing of musical and arithmetic structures. Our main finding was the observation of interactive influences between music and arithmetic structure processing, in particular for large problems. This finding suggests that music and arithmetic structure processing share cognitive resources dedicated to structural and temporal integration processes, as it has been previously suggested for language and music processing (Fedorenko et al., 2009; Hoch et al., 2011; Koelsch et al., 2005; Slevc et al., 2009; Steinbeis & Koelsch, 2008), as well as for language and arithmetic processing (Baldo & Dronkers, 2007; Fedorenko et al., 2007; Martín-Loeches et al., 2006). Together with previous research on music and language processing, and on arithmetic and language processing, our study led to the hypothesis that music, arithmetic *and* language structure processing tap into a common pool of cognitive resources. These resources may be required for structural integration of information over time, notably to link events according to knowledge-based rules (e.g., rules of Western tonal music, arithmetic rules or syntactic rules in language) into coherent sequences (Hoch, Tillmann, & Poulin-Charronnat, 2008; Martín-Loeches et al., 2006). Future research will need to further investigate the domain-generality of these temporal and structural integration resources: These resources might be more general than for music, language and arithmetic processing and also apply to the processing of other sequence types that are governed by knowledge-based rules, such as newly acquired rule-based sequences (Lelekov, Dominey, & Garcia-Larrea, 2000; Lelekov-Boissard & Dominey, 2002) or human actions (Fazio et al., 2009; Jackendoff, 2009). Recent studies have just started investigating these predictions (e.g., Sammler et al., 2010 for music and action).

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