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Is there a domain-general cognitive structuring system? Evidence from structural priming across music, math, action descriptions, and language

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ABSTRACT

Cognitive processing in many domains (e.g., sentence comprehension, music listening, and math solving) requires sequential information to be organized into an integrational structure. There appears to be some overlap in integrational processing across domains, as shown by cross-domain interference effects when for example linguistic and musical stimuli are jointly presented (Koelsch, Gunter, Wittfoth, & Sammler, 2005; Slevc, Rosenberg, & Patel, 2009). These findings support theories of overlapping resources for integrational processing across domains (cfr. SSIRH Patel, 2003; SWM, Kljajevic, 2010). However, there are some limitations to the studies mentioned above, such as the frequent use of unnaturalistic integrational difficulties. In recent years, the idea has risen that evidence for domain-generality in structural processing might also be yielded though priming paradigms (cfr. Scheepers, 2003). The rationale behind this is that integrational processing across domains regularly requires the processing of dependencies across short or long distances in the sequence, involving respectively less or more syntactic working memory resources (cfr. SWM, Kljajevic, 2010), and such processing decisions might persist over time. However, whereas recent studies have shown suggestive priming of integrational structure between language and arithmetics (though often dependent on arithmetic performance, cfr. Scheepers et al., 2011; Scheepers & Sturt, 2014), it remains to be investigated to what extent we can also find evidence for priming in other domains, such as music and action (cfr. SWM, Kljajevic, 2010). Experiment 1a showed structural priming from the processing of musical sequences onto the position in the sentence structure (early or late) to which a relative clause was attached in subsequent sentence completion. Importantly, Experiment 1b showed that a similar structural manipulation based on non-hierarchically ordered color sequences did not yield any priming effect, suggesting that the priming effect is not based on linear order, but integrational dependency. Finally, Experiment 2 presented primes in four domains (relative clause sentences, music, mathematics, and structured descriptions of actions), and consistently showed priming within and across domains. These findings provide clear evidence for domain-general structural processing mechanisms.

1. Introduction

At first glance, language and music might appear to be two fundamentally different skills. Whereas language is assumed to be our primary means for communication, music is often considered a skill that is explicitly acquired for leisure and self-expression. Consequently, both the functionality and the innateness of these two domains seem to differ largely, and the meaningful elements as well as the syntactic rules governing them can be easily differentiated (cfr. Peretz & Coltheart, 2003). As such, it seems intuitive to treat both domains of processing as being independent of the other.

In contrast to these intuitions, it has often been suggested that there are many commonalities in the psychological underpinnings of music and language (Fedorenko, Patel, Casasanto, Winawer, & Gibson, 2009; Patel, 2008), and that a modular view might be unwarranted. When investigating modularity in cognition (cfr. Barrett & Kurzban, 2006), it has become clear that in order to determine whether two domains of cognitive functioning are separated, it is important to regard the specific *operations* that are performed on the received information. Indeed, it can be stated that whereas both the sort of information and the rules by which this information is processed are largely different between both domains, the acquisition and application of structuring processes is very similar.

People are exposed to both language and music on a daily basis. Behind the seemingly effortless perception of music, is a set of

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complex cognitive processes that analyze the incoming sound sequences. The musical rules governing these processes are implicitly learned from early infancy through repeated exposure (Trainor & Trehub, 1994). These characteristics can be just as easily applied to language learning. Upon comparing the two domains, behavioral (Perruchet & Poulin-Charronnat, 2013) and electrophysiological (Koelsch, Gunter, Wittfoth, & Sammler, 2005) studies suggest considerable overlap in structural processing. For instance, when presenting music and linguistic stimuli simultaneously, an unexpected (out of key) chord increases the reading time cost for a syntactically unexpected word vs. expected word; but effects of semantic violations are not enhanced (Slevc, Rosenberg, & Patel, 2009, but see effects on semantic garden path unexpectancies, Perruchet & Poulin-Charronnat, 2013). Additionally, functional imaging studies demonstrated activation in similar regions of the brain (i.e., the left and right Inferior Frontal Gyrus) during the presentation of music-syntactic irregularities (Tillmann, 2012) and syntactically incorrect sentences (Friederici, Rüschemeyer, Hahne, & Fiebach, 2003). Such commonalities suggest that music and language processing share some of their processing principles.

An account for these findings of overlap is provided by the Shared Syntactic Integration Resource Hypothesis (SSIRH, Patel, 2003). The SSIRH claims that both musical and linguistic sequences are integrated into higher order structures based on acquired syntactic rules. Whereas these syntactic rule representations are domain-specific, the execution of these rules – which is required to accurately process the sequential information – makes a demand on overlapping resources. The domain-specific rule representation networks allow for each domain to be impaired in isolation (cfr. Peretz & Coltheart, 2003), whereas the resource overlap would lead to interactions when both modalities are processed concurrently (e.g., Slevc et al., 2009) (see Fig. 1).

In the SSIRH, the idea of syntactic integration (Patel, 1998, page 3) is expressed as: "the linking of the current input to past dependents in a string, with the assumptions that this integration is more costly when dependencies are more distant, when they must reactivate dispreferred structures, or when they are simply impossible". In stating that the resources underlying "structural integration mechanisms" are shared across music and language, the SSIRH model thus proposes that dependency processing in both domains is based on a common (and limited) processing capacity.

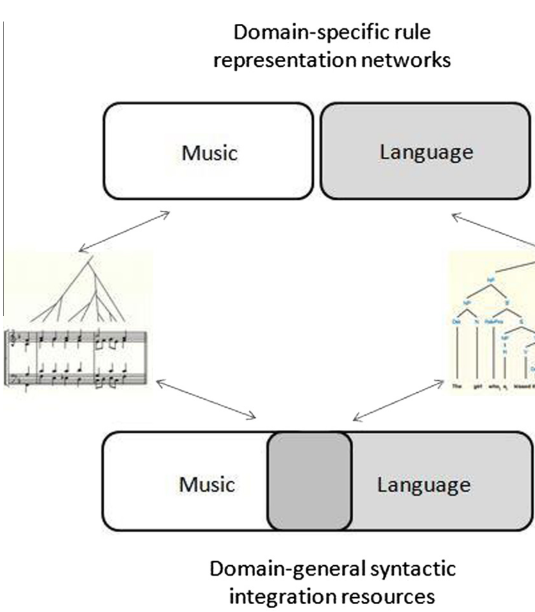

Fig. 1. Representation of the SSIRH hypothesis (Patel, 1998, p. 675). Whereas language and music both entail domain-specific formal knowledge networks, the structural integration of information processing in both domains is very similar. Therefore, it is suggested that whereas the rules on which this integration is based are domain-specific, the resources that support this integration might not be.

It is important to address how this "dependency processing" can be aligned with current structural processing theories in both tonal harmony and language. As presented by Rohrmeier (2011), the structural processing of music is indeed based on dependency principles. More specifically, it is argued that each musical element in a sequence can have structural connections to preceding or succeeding elements through dependency relationships. It is stated that the elements within a harmonic melody will form a structural "head" through these recursive dependency relationships, thus further integrating new elements in the established structure. Importantly, this principle also entails that a long-distance dependency can be formed across other functional elements, thus structuring the harmonic melody into a tree-like constitution. For more information, see Rohrmeier (2011) and the GTTM model of music theory (Lerdahl & Jackendoff, 1983). Clearly, such musical theories largely resemble the idea of dependency processing in language, as expressed in models such as the Dependency Locality Theory (Gibson, 2000). According to Gibson's (2000) DLT, the structuring of linguistic materials depends on two mechanisms. First, the structure, including all incomplete dependencies, needs to be maintained in memory. Second, new incoming elements need to be structurally integrated with the structure created thus far. DLT further argues that when there is a larger distance between two elements that need to be integrated, structural integration becomes more difficult. Both mechanisms within the DLT are based on working memory resources, and it might be argued that the "syntactic integration resources" presented in the SSIRH (Patel, 2003) might very well be considered as resources allowing for dependency processing. Similarly to Patel's description of the "structural integration resources", Gibson states that the structural processing of sentences is largely based on the principle of locality, meaning that the cost of integrating two elements which are structurally related to each other will increase with the distance between these two elements. In summary, in line with the SSIRH (Patel, 2003), both musical and linguistic theories include dependency processing as a key mechanism in structural processing, assuming that more syntactic working memory resources will be required for dependencies that involve larger distances across elements in the sequence.

In recent research, the idea of overlapping syntactic working memory resources involved in structural integration across domains has been elaborated upon in the Syntactic Working Memory theory of Kljajevic (2010, SWM).

This theory claims that constructing a partial structural representation through the integration of available structural information might critically depend on domain-general syntactic working memory resources. This SWM could then be construed as an interface between domain-specific rules stored in the long-term memory and rapid working memory processes involved in the processing of dependencies between elements along these rules (cfr. SSIRH, Patel, 2003). Indeed, the theory of syntactic working memory (cfr. Kljajevic, 2010) has extended its role beyond language to include music and arithmetic (Fiebach, Schlesewsky, Lohmann, von Cramon, & Friederici, 2005). The SWM (cfr. Kljajevic, 2010; Fiveash & Pammer, 2012) could be a domain-general interface acting upon domain-specific rule representations, an idea which strongly aligns with previous behavioral (e.g., Fedorenko et al., 2009) and neurological (e.g., Patel, Gibson, Ratner, Besson, & Holcomb, 1998) evidence in favor of the SSIRH (Patel, 2003).

In a recent experiment, Fiveash and Pammer (2012) have explored whether music and language both draw on SWM by looking at the interaction between unexpected elements in music and the working memory involved in word list and complex sentence processing. Importantly, it was found that the (syntactic) working memory capacity available to sentence processing was decreased by the musical unexpectancies, whereas no decreased performance was found on the word lists (which are claimed not to require syntactic working memory). This recent study is in line with other studies, trying to provide evidence for the SSIRH and other models suggesting domain-generality in dependency integration through interference paradigms (e.g., Slevc et al., 2009). In these studies, listeners typically simultaneously process linguistic and musical stimuli containing unexpected elements. However, one can ask to what extent the idea of overlapping structural processing can also be investigated beyond the use of interference in structural difficulty resolution. In particular, both linguistic and musical integration processes regularly require the processing of dependencies between symbols across a short or long distance in the string. Studies on structural priming in language processing suggest persistence in syntactic decisions concerning such dependencies.

Traditionally, structural priming entails that processing a sentence with a particular syntactic structure (e.g., a passive) increases the chance that such a structure will again be used on the next trial (e.g., Bock, 1986; see Pickering & Ferreira, 2008, for a review). Structural priming has been shown to tap into syntactic processes during sentence comprehension and production; it does not require overlap in lexical items or thematic roles (Bock, 1986; Ferreira & Bock, 2006; Pickering & Ferreira, 2008) and does not depend on a similar prosody between prime and target (Bock & Loebell, 1990). It has been shown for many syntactic constructions (Loncke, Van Laere, & Desmet, 2011; Rowland, Chang, Ambridge, Pine, & Lieven, 2012), in many languages (Bock, 1986; Ferreira & Bock, 2006) and between the languages of bilinguals (Desmet & Declercq, 2006; Hartsuiker, Pickering, & Veltkamp, 2004; Loebell & Bock, 2003). There are several accounts of structural priming, which all have in common that the effect concerns syntactic representations. For instance, Pickering and Branigan's (1998) influential account assumes localist syntactic representations connected to verbs. Thus, a representation for the verb *to give* would be connected to nodes representing the double-object dative ("give the child some candy") or a prepositional object dative ("give some candy to the child"). Chang, Dell, and Bock (2006) proposed a model that considers priming to be a result of error-based, implicit learning of syntactic representations. Processing a prime sentence in conjunction with a particular type of message would lead to an update of syntactic units in a distributed connectionist network; as a result, choosing that structure would be more likely on a new occasion. Thus, these accounts assume priming to be a result of the activation of structural integration representations (for a review, see Pickering & Ferreira, 2008).

However, Scheepers (2003) reported a type of structural priming that does not fit so easily with the notion of priming a specific syntactic representation (such as the representation of a phrase structure; Pickering & Ferreira, 2008). In particular, this study primed the structural choice of attaching a relative clause to a noun that was mentioned early (lights) or late (room) in sentence beginnings such as "I saw the lights of the room that...". Given the ambiguous sentence beginning, the participant could complete the sentence as a high attachment (HA) structure (attaching the relative clause to the first noun: "I saw the lights of the room *that were bright*") or low attachment (LA) structure (attaching the relative clause to the second noun, which is embedded in the prepositional phrase: "I saw the lights of the room *that was large*") relative clause, a response choice that could be primed by preceding relative clause attachments. These types of sentences differ at the global structural level, given that the difference cannot be represented by representations at a lexical level, or by sets of syntactic rules that are unique for each sentence (Scheepers, 2003). That is, there are no phrase structure rules tied to a specific lexical item, that express the difference between a high-attachment and low-attachment sentences. It is even the case that both sentences can be generated by the same set of phrase structure rules, albeit it applied in a different order. Thus, the relevant structural contrast concerns the hierarchical configuration of modifiers in the syntactic tree representation, and not the particular rules which need to be applied to construct this representation. Further studies showed relative clause attachment priming occurs across languages (i.e., Dutch and English; Desmet & Declercq, 2006), and sentence structures (i.e., between the attachment of Prepositional phrases and relative clauses; Loncke et al., 2011).

How does attachment priming come about? Scheepers argued that attachment priming might be driven by the sequential order with which syntactic rules are applied. However, that account does not fit with the finding of attachment priming across different structures, as the rules for creating a prepositional phrase and relative clause differ; see Loncke et al. (2011). It is possible that attachment priming results from priming an abstract, hierarchical structure (independent of the internal details of this structure) or from priming of the height of attachment (low or high). Most importantly for our purposes, this form of hierarchical construction priming thus relates to the influence of structural integration mechanisms which process dependencies between the elements of a sequence, regardless of the specific syntactic rules on which such integrations are based (cfr. SSIRH). This argument is strongly supported by a recent study of Scheepers et al. (2011), which reported evidence for attachment priming from simple arithmetic problems to sentence completion, although the occurrence of priming depended on the participants' arithmetic skills (e.g., the hierarchical structure of mathematical equations such as "$3 + (2 * (2 + 3))$" versus "$3 + ((2 * 2) + 3)$" corresponds to low and high attachment structures respectively). Furthermore, a recent study (Scheepers & Sturt, 2014) found that if linguistic structure was incongruent with that of a math equation, the probability increased that participants solved the equation incorrectly. In summary, recent studies suggest that attachment priming (Scheepers, 2003) can be found across languages and sentential structures, and even across domains (Desmet & Declercq, 2006; Loncke et al., 2011; Scheepers et al., 2011; Scheepers & Sturt, 2014).

Therefore, the attachment priming procedure (Scheepers, 2003) might prove a worthwhile means to investigate possible overlap in structural processing mechanisms of music and language. The suggestion of dependency priming within and across domains seems to resonate with either priming of a representation of a full syntactic configuration or of the position (early or late) of attachment. Importantly, further studies (Scheepers et al., 2011; Scheepers & Sturt, 2014) showed that such priming of dependencies generalizes across domains, so that relative clause attachment can be affected by the structure of an arithmetic problem. It is therefore conceivable that one can find priming effects between musical and linguistic stimuli, supporting the notion of a Syntactic Working Memory (SWM, Kljajevic, 2010) that is shared across domains, and which has been frequently linked to models such as the SSIRH which hypothesize domain-general systems (cfr. Fiveash & Pammer, 2012).

The aim of this paper thus is to test the hypothesis that the processing of dependencies can persist between the domains of music and language processing. Such persistence would be convincing new evidence for the SSIRH (Patel, 2003, 2008) and related proposals such as the SWM (Kljajevic, 2010), because it would indicate that the musical and linguistic domains overlap in an important aspect of structural integration (i.e., dependency processing). Importantly, a priming effect would strongly suggest that processing in one modality affects processing in another one (i.e., a causal conclusion) and it would do so without the added complications of having a dual-task setup and unexpected musical and/or linguistic stimuli as is typical in current unexpectancy-based interference paradigms. The latter aspect is particularly important in light of recent proposals that consider the shared resources of the SSIRH as resources for error processing and repairing (Slevc & Okada, 2015).

It is important to note that the auditory sequences we will present in these experiments are not strictly speaking musical sequences: the sequences were not written by a human composer but by a computer program and they did not follow the standard harmonic rules of Western music. We did this to be able to tap into music processing mechanisms that every individual exposed to Western culture will pick up implicitly, rather than the specific set of skills and knowledge that pupils acquire during formal music education. This has the advantage that our results can be generalized more broadly than only to musical experts. One implication though is that while we will sometimes use the terms *melody* and *music* to refer to our stimuli (for example, in our participant debriefings), we acknowledge that a more precise denomination would be 'pitch sequence'.

Experiment 1a tested the hypothesis that there is overlap in structural processing mechanisms between language and music. We predicted a structural priming effect between these domains so that processing a dependency in the pitch sequence would affect the subsequent processing of a dependency when completing a sentence (i.e., attachment of a relative clause). In particular, pitch sequences contained either one or two boundaries between pitches, resulting in an ABA vs. ABB sequence. Crucially, we argue that the third subsequence can be considered a continuation of the first in the ABA sequence, and as a continuation of the second in the ABB sequence; thus, such sequences would be analogous in their structure of dependencies to a high- vs. low-attachment sentence respectively, and we would expect structural priming from these sequences to relative clause attachment completion. A control experiment (Experiment 1b) presented the same target stimuli, but replaced the primes with sequences of color patches. Color sequences were also organized into ABA and ABB sequences, but in this case there is no reason to assume dependency between the third and first or second subsequence. If any priming effect in Experiment 1a is based on only the superficial chunking of elements into ABA or ABB order, we expect a priming effect here too. But if cross-domain priming requires the processing of dependencies there should be no effect here. The SSIRH is only concerned with the relation between music and language. A fascinating possibility would be that other cognitive domains would use the same domain-general mechanism (Kljajevic, 2010; Scheepers et al., 2011). Experiment 2 therefore not only included primes created in the musical domain, but also in the domains of non-syntactic sentential dependencies (i.e., means end parsing; Allen, Ibara, Seymour, Cordova, & Botvinick, 2010) and math (Scheepers et al., 2011; Scheepers & Sturt, 2014). To compare cross-domain priming to within-domain priming, we also included relative clause sentences as primes. If structural processing is shared across all these domains, we expect to see structural priming across all the tested domains.

2. Experiment 1a

2.1. Method

2.1.1. Participants

We recruited 30 participants from the Ghent University student pool (18 years of age on average; 3 male, 27 female participants), all native speakers of Dutch; they participated in exchange for course credits. Sample size was decided upon a-priori. Participants were recruited regardless of their musical expertise. We ran participants until the predetermined sample size of 30 was reached. Due to data transfer problems, two recordings were unusable, and a sample of 28 participants was retained.

2.1.2. Materials

The sentence beginnings were construed in Dutch. We created 60 critical sentence beginnings with an ambiguous sentence structure such as "I saw the knives in the kitchen that", which can be completed to a high-attachment (HA) structure ("were sharp") or a low-attachment (LA) structure ("was dirty"). There were also 20 filler sentences with an unambiguous sentence structure. By this, we mean sentences which, following the gender-specific pronoun, could only be completed in one syntactically correct fashion (by analogy, in English, a sentence like "I saw the knives of the cook who ...") Because the first and second noun in the critical sentences always differed in number, verb number provided an objective and straightforward way to categorize the sentence completions (in contrast to English, Dutch very transparently marks number on verbs). For example, the sentence "I saw the knives in the kitchen that..." verbally completed by "*was* dirty" is judged as a LA completion given that the verb "*was*" is singular and thus must refer to "the kitchen". The sentences can be found in the project materials registered on the Open Science Framework (http://openscienceframework.org/profile/v49bp).

The pitch sequences used as structural primes consisted of eight tones each. The tones were computer-generated sine waves with a duration of 230 ms. Their frequencies ranged from 196.00 to 698.46 Hz and corresponded to 18 tones: G3, Ab3, A3, B3, C4 (i.e., middle C, =261.63 Hz), Db4, Eb4, E4, F4, and the same tones one octave higher. Tones were separated by 70 ms silences.

To create the structures, we differentiated three clusters of harmonically congruent pitches: *A E B*|*F C G*|*Eb Ab Db*, represented on the Circle of Fifths for Western musical keys in Fig. 2. These pitch clusters were chosen by taking the tonic of 3 adjacent musical keys. As can be seen, these pitch groupings can be regarded as separate "clusters" which encapsulate neighboring keys on this Circle of Fifths, indicating a strong harmonic congruency between the tones within a cluster. Furthermore, the clusters are separated by

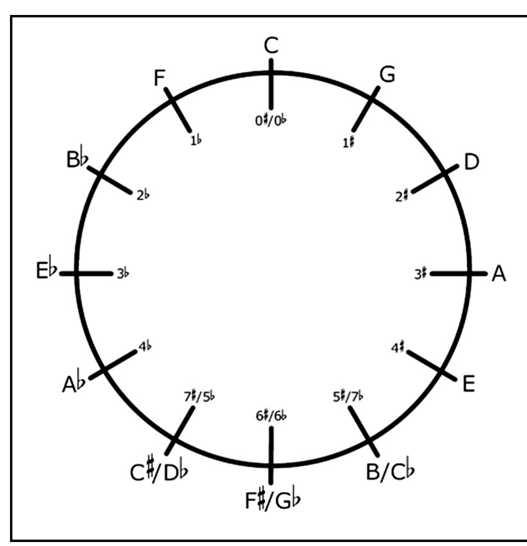

Fig. 2. The clusters |A E B|, |F C G|, and |Eb Ab Db| consist of tones that are close to each other on the Circle of Fifths for Western musical keys. In comparison, switches between clusters would entail at least 2 or more steps on this Circle of Fifths. Given that the circle represents harmonic closeness of Western musical keys, the figure illustrates how, even though there are no harmonic rules to the pitch cluster creation, pitch transitions within clusters sound more "neighboring" on average than pitch transitions between clusters.

one step on the Circle of Fifths for Western musical keys. It is plausible that while participants tap into implicit knowledge about key distance relationships, even though the clusters themselves do not correspond to any established music-theoretic construct. Importantly, though these clusters are thus strongly based on the participant's previous exposure to Western tonal harmony, the pitch clusters themselves will have to be acquired in the experiment, as they do not correspond with any categorization that can be made on the basis of knowledge of formal music theory. Therefore, the pitch sequences cannot be processed in terms of formal musical knowledge and regardless of their musical abilities, all participants would start learning these categories implicitly from the start of the experiment onwards. Due to the consistent manipulation of the pitch clusters, we expected participants to rapidly acquire implicit experience with the clusters.

The occurrence of cluster shifts was used to parse sequences of pitches, thereby creating a musical analogy to the dependency structure of a high or low attachment structure in the pitch sequence. In pitch sequences resembling the high-attachment dependency structures, there was a cluster shift between the 3rd and the 4th and between the 6th and the 7th tones (e.g., *EAB|GCG|EB*), thus creating an ending that is related to the beginning (similar to "the lights/of the room/that were broken"). In these pitch structures the second cluster shift always consisted of a transition to the initial cluster of the sequence. To resemble LA dependency structures, there was a cluster shift only between the 3rd and the 4th tones (e.g., *EBA|GCFGC*), thus creating a clear 2-chunk structure (similar to "the lights/of the room that was spacious"). Importantly, a "cluster shift" entails that a pitch is randomly selected outside the current pitch cluster. However, given that pitch clusters are based on their harmonic congruency on the Circle of Fifths, rather than their frequency in Hz, such a "cluster shift" transition between tones did not result in a larger shift in tone frequency than transitions within the same clusters (e.g., "A–Ab" would be a cluster shift transition, but is in fact a smaller transition in frequency than "A–E", which would be a transition within the same cluster"). Therefore, the cluster shift transitions had no differences in frequency, amplitude or duration as compared to within cluster transitions, apart from the implicit clustering which constituted the pitch sequences.

An example of the materials is presented in Fig. 3. To validate whether the pitch sequences were indeed structured by pitch clusters, we applied a probe recognition task, which is explained in the following section.

2.1.3. Probe recognition task

To determine whether pitch cluster processing occurred as expected, we adapted a harmonic processing task introduced by Tan, Aiello, and Bever (1981). These authors (cfr. Fig. 4) found that participants were less able to correctly recognize two tones as presented sequentially when these tones were separated by a harmonic boundary, as compared to when they were both within the same harmonic phrase of the melody. Similarly, we argued that, if the pitch sequence would indeed be structured according to cluster shifts, participants' correct recognition of a two-pitch probe would be lower if the probe consisted of two pitches spanning a cluster shift.

After each prime, a recognition task was presented on which participants judged whether a two-pitch probe had been presented in the preceding pitch sequence. This recognition probe either consisted of two tones that had not been presented at all (*foils*, 1/3 of trials), two tones that had been presented in that order and did not include a pitch boundary (*within*, 1/3 of trials), or two tones that had been presented in that order presented, but did include a transition between clusters, and thus a pitch boundary (*between*, 1/3 of trials). As in Tan et al. (1981) we expected two tones separated by such a boundary to be recognized less well (if this boundary was indeed processed as intended).

2.1.4. Design

In 60 of the 80 sentences, the sentence beginnings were ambiguous so that both a HA or LA relative clause structure would be a valid completion. The other 20 sentence beginnings were fillers, in which the sentence beginning was unambiguous (10 HA, 10 LA) so as to force all participants to use both HA and LA structures as completions. The pitch sequences either had a structural analogy to a HA structure (50% of critical trials and fillers) or to a LA structure (50% of critical trials and fillers). The pitch sequences were randomly created for each participant, and the type of structure of the pitch sequence was counterbalanced across participants for each sentence.

2.1.5. Procedure

The participants performed 80 trials (fully randomized), with each trial consisting of a pitch recognition task and a sentence completion task. For the first task, participants listened to 8-pitch sequences through headphones. To ensure attentive music processing and validate the cluster manipulation, there was a recognition task after each pitch sequence. During the recognition task, the background color of the screen changed from black to blue, and participants heard a two tone fragment; they judged whether this two tone fragment had occurred in the previously heard pitch sequence. After this judgment (performed by pressing "f" or "j" for wrong or right, respectively), an incomplete sentence was presented on the screen, for instance "*Iemand waarschuwde de familie van de kinderen die*..." ("Someone warned the family of the children who..."). Participants were asked to repeat and complete this sentence fragment out loud, and their responses were recorded for later processing. To conceal the goal of the experiment, participants were given the following instruction: "*the sentences are being recorded as stimulus materials to use in later experiments focusing on sentence endings. The music recognition task is separately analyzed. Yet for this experiment, music and language tasks are interwoven to allow a better differentiation between ongoing and previously heard melodies*". In a debriefing after the experiment, none of the participants indicated to have been aware of the priming manipulation.

2.1.6. Analyses

After data collection, the sound recordings (containing the full sentence productions of the participants) were individually rated. The structure of these attachments was categorized, and only then was the response added as a variable to the larger data sheet which included the condition and priming structure. Given that all primes were visually presented, or auditorily through headphones, no information about the prime condition was thus available to the rater when scoring the sentence completion, so as to provide a 'blind' rating setting. The native tongue of the rater was Dutch. After collecting the dataset, we ran linear mixed effect (LME) analyses on two dependent variables: the performance on the probe recognition task and the structure of the sentence completion.

For the probe recognition performance, the independent variables "prime structure" (i.e., HA or LA structures pitch sequences), "response" (i.e., the structure of the sentence completion, HA or LA), and "probe" (i.e., the kind of recognition probe: within|between|foil) were introduced to the model. First, we defined a standard model with only random intercepts across subjects and target sentences. We chose to always include the random intercepts in our baseline model. Then, we incrementally determined the optimum lmer model by testing the contribution of random slopes for our three independent variables over both subjects and items. No random slopes contributed significantly, thus the standard lmer model with only random intercepts was kept. Then we

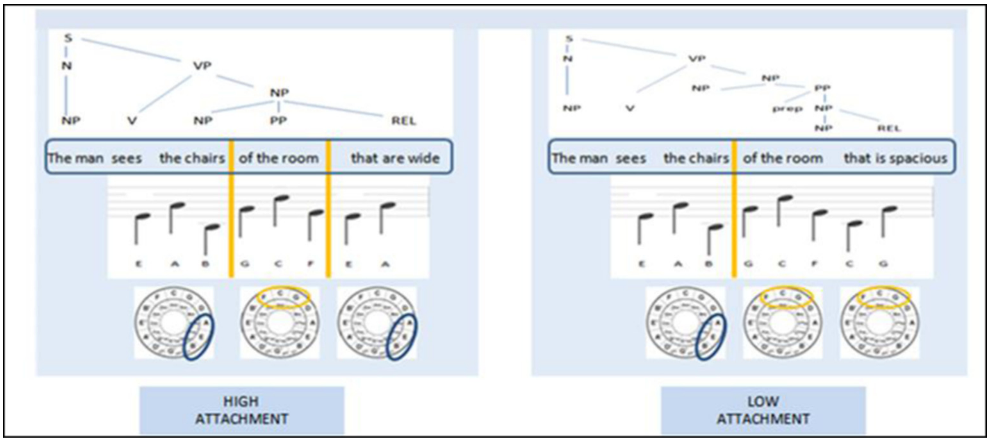

Fig. 3. Overview of the materials. Whereas high attachment dependency stimuli are characterized by two 'shifts' leading to an ABA-like structure with a return to the root cluster, the low attachment dependency stimuli are characterized by only one 'shift' leading to an ABB-like structure without a return to the root cluster.

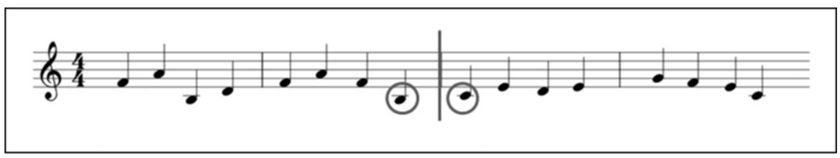

Fig. 4. Example of the harmonic integration measure as reported by Tan et al. (1981). Participants were presented with melodies that included a harmonic boundary splitting the melody up in two phrases. When asking the participants to assess whether a two-tone probe represented a tone transition that was presented in the melody, Tan et al. found that it was harder to recognize the tone transition when it encompassed the harmonic boundary (i.e., presenting the two tones in circles as the two-tone probe). This difference in probe recognition of tone transitions within versus between harmonic transitions is argued to represent a harmonic structural processing effect.

incrementally determined the variables which significantly improved the lmer model. The results of this model are reported below.

For the sentence completion performance, the independent variables "prime structure" (i.e., HA or LA structures pitch sequences), "correct" (i.e., the performance on the recognition task), and "probe" (i.e., the kind of recognition probe: within|between|foil) were introduced to the model. Using the same method as reported above, we found that no random slopes significantly contributed to the standard random intercept model. After incrementally determining the contribution of each independent variable, we determined the best fit of our lmer model, which included only "prime" as an independent variable. The results of this model are reported below.

All analyses were ran on R (version 3.0.3), using the lme4 package (version lme4_1.1-7). The data files and the R script that was used are freely available on http://opensciencefraemwork.org/profile/v49bp.

2.2. Results

2.2.1. Tone probe recognition task

The participants correctly rejected 78% of the *foils* and correctly accepted 74% in the *within* condition but only 68% in the *between* condition. The clear above-chance performance (50%) overall demonstrates that the participants processed the musical stimuli attentively. The 6% difference between the *within* and *between* conditions was significant, ($\beta = 0.306$, $z = 2.228$, Pr $(>|z|) = 0.026$). This confirms that the participants indeed processed the cluster shifts (Tan et al., 1981) and thus serves as a manipulation check. There was no significant effect of trial progression (early versus late in the experiment) on pitch recognition performance, suggesting quick learning of the pitch clusters.

2.2.2. Sentence completion task

Spoken sentence completions were recorded, transcribed, and scored. To count as a LA or HA completion, we based ourselves on the grammatical number of the verb used in the completion, which is overtly marked in Dutch. We needed to discard 2% of the targets due to mumbling or silences. Importantly, pitch sequence structure (high or low attachment dependencies) significantly predicted linguistic choices ($\beta = 0.233$, $z = 1.994$, Pr $(>|z|) = 0.046$). There were 61% LA responses after a HA melody, but 65% LA responses after a LA melody, a 4% cross-modal structural priming effect. Again, including trial progression did not significantly improve the model fit, and was thus discarded. It is important to acknowledge that – while reaching significance – the priming effect was rather small. However, this is not uncommon to even within-language syntactic priming effects (cfr. Rowland et al., 2012, finding priming effects between 3% and 7%). An exploratory, subsidiary analysis of Experiment 1 – which considered the previous target response as a factor influencing target completion – revealed an interaction between the previous response and the prime ($\beta = 0.505$, $z = 2.074$, Pr $(>|z|) = 0.038$), showing that HA-primes increased HA-responses more strongly when the previous response was a HA-sentence (9% priming) than when it was a LA-sentence (no priming).

2.3. Discussion

Experiment 1a showed a structural priming effect from the pitch sequences to later sentence completion, consistent with our hypothesis that there can be priming of domain-general dependencies. However, we need to make an important remark concerning these results. In the previous studies concerning attachment priming (e.g., Scheepers, 2003; Scheepers et al., 2011; Scheepers & Sturt, 2014), the priming structures, whether linguistic or mathematic, have always consisted of an abstract structure in which the processing of hierarchical structure was paramount to an accurate comprehension of the prime. However, the pitch sequences provided in Experiment 1a are experimentally manipulated, and while the high and low attachment dependency structures differ in the manner to which the pitch sequence returns to the root pitch cluster, this might not have a hierarchical nature. Perhaps it is possible that the order of presentation ("A B A" versus "A B B") suffices to create relative clause priming effects, but on the level of superficially chunking the elements instead of a dependency level. To address the possibility that such chunking processes might drive the priming effect of Experiment 1a, we now report a control experiment in which "high attachment" and "low attachment" chunked color sequences were used (e.g., red–blue–red for HA and red–blue–blue for LA).

3. Experiment 1b: color sequence control

3.1. Method

3.1.1. Participants

To obtain a participant sample that is comparable to that of Experiment 1a, we recruited 40 participants from the Ghent University student pool (18 years of age on average; 12 male, 28 female participants), all native speakers of Dutch; they participated in exchange for course credits. Sample size was determined so that the power exceeded that of Experiment 1a. Participants were recruited independently of their musical expertise. We ran participants until the predetermined sample size of 40 was reached.

3.1.2. Materials

The 80 sentences – both target and filler sentences – were identical to Experiment 1a. To create the priming structures, sequences of three colored squares were presented. These three colors were selected from 9 colors: light, regular, and dark variations of red, blue, and green. These were created by selecting 180, 210, and respectively 240 on each of the three positions of the RGB color chart. Similar to the pitch sequences, the color sequences had 50% HA and 50% LA structured sequences. In the LA sequences, the third color matched the hue (but not the shade) of the second color, yet not the first color, resulting in an "ABB" pattern of colors. In the HA sequences, the third color matched the hue (but not the shade) of the first color, yet not the second color, resulting in an "ABA" pattern. Each color square was 200×200 pixels in size on a 1280×1024 pixel screen. Squares were presented on a black background. Importantly, the duration with which the three colors were presented exactly matched the duration of the segments within the pitch sequences of Experiment 1a. More specifically, the first two colors were presented for the duration of what would in Experiment 1a be the first two (three-tone) phrases, whereas the last color was presented for the duration of what would in Experiment 1a be the last (two-tone) phrase. Thus, the priming stimuli were analogous to those of Experiment 1a in that overlapping subsequences (e.g., the first and third subsequence in ABA) were members of the same category (e.g., "red", EBG-cluster) but were never identical and in the overall time course of presentation.

3.1.3. Probe recognition task

To provide a probe recognition task comparable to that in the previous experiment, participants were asked to indicate if a certain shade of color had been presented in the color sequence. Similarly to Experiment 1a, this task required participants to process the prime stimulus attentively, while not focusing attention directly to the overall structure. The probe color would be a previously presented color in 50% of trials, and a foil probe in the other 50% of trials. If the probe color was a foil, it was randomly picked from all available colors and color shades which were not presented (i.e., approximately 50% wrong color, and 50% wrong color shade).

3.1.4. Procedure

The procedure was identical to that of Experiment 1a, with the exception that instead of the auditorily presented pitch sequences, participants now received the visually presented color sequences, which were matched in duration to the pitch sequences in Experiment 1a. Furthermore, participants responded to the probe recognition task after prime processing. They were presented with the target color shade for the exact duration of the probe sequence in Experiment 1a. This way, the responses and inter trial interval between prime and target were kept exactly the same for both Experiments 1a and 1b.

3.1.5. Analyses

After data collection, the sound recordings (containing the full sentence productions of the participants) were individually rated for priming task accuracy and the dependency structure of sentence completions. The structure of these attachments was categorized, and only then was the response added as a variable to the larger data sheet which included the condition and priming structure. Given that all primes were visually presented, or auditorily through headphones, no information was thus available when rating the sentence completion, as to provide a 'blind' rating setting. The native tongue of the rater was Dutch. After collecting the dataset, we ran LME analyses on two dependent variables: the performance on the probe recognition task, and the structure of the sentence completion. The independent variables in each analysis and the method of incrementally determining the optimum lmer model and the best model fit are exactly corresponding with the analyses of Experiment 1a (see above). Importantly, the variables "prime" and "probe" from Experiment 1a are here replaced by two variables. Instead of "prime", we used the chunking structure of the color sequence (either ABA or ABB structured), and instead of "probe" we used "color probe question", indicating whether the recognition probe was a foil or not.

For the probe recognition performance, the optimum lmer model included, apart from random intercepts, also a random slope for "color question" (i.e., whether the recognition probe was a foil or not) over subject. Following this lmer model, best model fit was achieved by only including "color question" as an independent variable for recognition performance. The results of this model are reported below.

For the sentence completion task, the optimum lmer model only included the random intercepts. No independent variable contributed to the model fit. However, upon including the "previous response" as an independent variable, there was a tendency ($p = 0.10$) for an improved fit when the model included "color structure" (ABA versus ABB structure) and "previous response" (i.e., the attachment structure of the sentence completion on the previous trial) as independent variables. The results of this model are reported below.

Finally, the data from Experiment 1a was added to that of Experiment 1b, and the variable "prime level" was created to differentiate between the sort of primes (dependency structure versus chunking structure). This way, it would be tested whether there was a significant priming difference between the two experiments.

All analyses were ran on R (version 3.0.3), using the lme4 package (version lme4_1.1-7). The data files and the R script that was used are freely available on http://openscienceframework.org/profile/v49bp.

3.2. Results

3.2.1. Color probe recognition task

There was no significant effect of type of color probe (correct or wrong, meaning whether or not the shade was present in the actual priming sequence). The performance on both correct and wrong color shades (71% for wrong shades and 76% for correct shades, where 50% would be chance performance) reflected similar levels of difficulty as in the recognition task of Experiment 1a.

3.2.2. Sentence completion task

No significant effects of prime structure on relative clause completion was found (where ABA-structured color primes yielded 59.36% LA completions, ABB structured color primes yielded 57.84% LA completions). However, we did find a marginally significant ($\beta = 0.1845$, $z = 1.676$, Pr $(>|z|) = 0.09$) tendency for priming from relative clause completions on the previous trial.

3.2.3. Contrasting Experiments 1a and 1b

Analyses of the joined dataset showed that "prime level" (i.e., whether the priming structure was a dependency structure of Experiment 1a or a chunking structure of Experiment 1b) was a significant predictor. Specifically, the priming effect found in Experiment 1a was significantly ($\beta = 0.332$, $z = 2.164$, Pr $(>|z|) = 0.03$) larger than in Experiment 1b.

3.3. Discussion

Experiment 1a showed a structural priming effect from the pitch sequences to later sentence completion. In the present control experiment using non-hierarchically structured sequences which display an ABA or ABB sequence, no priming effects were found. This provides evidence for our hypothesis that the priming effects found in Experiment 1a are based on the processing of dependencies and not on surface sequential order. This finding strongly supports our hypothesis for an overlap in the mechanisms processing both linguistic and musical structure,. Next, we conducted a further study to replicate and extend these preliminary findings. More specifically, we posed the questions whether this priming effect can be replicated, and to what extent it compares to within-domain priming.

Embedded in this larger experiment was a music-to-language priming condition, so that we could replicate the effect observed in Experiment 1a. To test the generality of cross-domain structuring mechanisms, we further extended our study with three other priming domains: non-syntactic (action-based) linguistic structure, mathematics and relative clause sentences (syntactic linguistic structure). Furthermore, we extended the study by not only including relative clause sentences, but also non-syntactically structured means-end sentences as targets. This way, we could directly compare priming within and across modalities.

4. Experiment 2

Experiment 2 presented prime sequences in four modalities: structured pitch sequences (cfr. Experiment 1a), sentences containing a relative clause structure (cfr. Scheepers, 2003), arithmetic equations (cfr. Scheepers et al., 2011), and sentences referring to goal-directed actions (thus including a non-syntactic attachment structure). When describing goal directed behavior, the sentence can be processed according to the "means end" structure of the described actions (Allen et al., 2010). For example, the sentence "*I close the curtains, take the scissors, and cut the paper*" contains two actions which directly address a goal (e.g., "close the curtains"), and one action which can be seen as a preparatory action (e.g., "take the scissors"). Therefore, following the means-end structure of the action description (i.e., grouping preparatory actions with the final action to which they are the means), dependencies will be created (e.g., a dependency between "cut the paper" and the previously uttered "take the scissors", which was the preparatory action to this means-end action). Importantly, these linguistic dependency structures are not related to syntax (i.e., the structures we test always consist of three conjoined clauses, irrespective of whether the third clause describes an action related to the first or second clause). It has been shown that the attachment structures of means end action descriptions can prime each other and are thus abstractly represented (cfr. Allen et al., 2010). We will refer to sentences with means-end parsing in action description as means-end sentences.

Additionally, participants completed target stimuli in two modalities: First, as in Experiment 1a, they completed sentence fragments that were ambiguous for attachment site. Second, they completed sentence fragments that were ambiguous for means-end structure.

4.1. Method

4.1.1. Participants

60. new participants from the student pool of Ghent University (19 years of age on average, ranging from 17 to 22; 10 male, 50 female), participated in exchange for course credits. Participants were run until the predetermined number of 60 participants was reached. As in Experiment 1, musical expertise was neither an inclusion nor an exclusion criterion. Furthermore, to account for possible influences of musical expertise, the amount of formal musical training was recorded for each participant; it ranged from 0 to 10 years (1.5 years on average), a factor that was included as an independent variable in the analyses.

4.1.2. Materials

Primes were constructed in four domains. First, there was a pitch sequence priming condition, in which the same stimuli as Experiment 1a were used and a recognition task similar to Experiment 1a was provided after each prime. In contrast to Experiment 1a however, the "foils" this time consisted of pitches that *were* present in the sequence, yet not in the specified order. This increased the difficulty of the recognition task as compared to Experiment 1a, given that participants would have to focus on the sequential order of the pitch sequence more to perform well on the recognition task.

Second, there was an attachment prime condition, in which the HA and LA structures were created by providing unambiguous sentence beginnings (e.g., "de kunstenaar maakte het logo van de artiesten die..."/"the artist made the logo of the musicians *WHO*..."), in which the gender agreement disambiguates the attachment of the following relative clause (the relative pronoun "die" refers to nouns preceded by the determiner "de", while the relative pronoun "dat" refers to nouns preceded by the determiner "het"). These items needed to be completed with a relative clause (cfr. Scheepers, 2003), resulting in LA or HA attachment. Thus, this prime condition in conjunction with relative clause attachment targets created a within-domain priming condition.

Third, there was a means end prime condition, in which the HA and LA structures were created through enabling/end actions (e.g., "grab the phone" is an enabling action, whereas "call the police" is the means end action). For example, "I take my phone, cover the wound, and call the police" would be a HA structured means end sequence, whereas "I cover the wound, take my phone, and call the police" would be a LA structured sequence. As was the case in the attachment prime condition, participants completed non-ambiguous means end sentences (e.g., "I take the toothbrush, clean the mirror, and...", where the means end completion can only plausibly form a HA structure). In conjunction with mean ends targets (see below), this prime condition created a second within-domain priming condition.

Fourth, we included an arithmetic equations condition, in which the HA and LA structured primes were adapted from the

Scheepers et al. (2011) study. In this condition, participants needed to solve equations as indicated by the use of brackets; "(2 + (2 ∗ (3 + 2))" for LA primes compared to "2 + ((2 ∗ 3) + 2)" for HA primes. The redundant brackets were used given the low performance accuracy of participants in a pretest phase.

Target fragments occurred in two domains: relative clause attachment and means end sentences. Targets were similar in structure to the primes in these domains, except that they were ambiguous and so could be completed either as a HA or a LA sentence.

4.1.3. Design

The 192 trials were made up of 48 trials in each of the four priming conditions (music, attachment, means end, and math), and in each condition, 24 primes had a HA structure and 24 a LA structure. The manipulation of priming domain and structure was crossed with target domain. Half of the targets consisted of ambiguous means end targets (e.g., "I take the scissors, plug in the USB, and...."), and the other half consisted of ambiguous attachment targets to be completed (e.g., "I see the lights of the room that..."). All manipulations of prime and target were within-subjects. The pitch sequences were randomly created for each participant, and the type of prime–target relation for each target item was counterbalanced across participants, so that each target was preceded equally often by each type of prime across all participants and each participant received the same number of trials in each combination of priming domain, target domain, and structure.

4.1.4. Procedure

The participants performed 192 experimental trials (24 HA and 24 LA structured primes in each of the four conditions), which were presented in a totally randomized order. Again, each trial consisted of a prime task and a sentence completion task. For the pitch sequence primes, the prime task was a simple pitch recognition task of a two-pitch probe (adapted from Experiment 1). For the syntactic attachment primes, participant vocally completed the visually presented unambiguous prime sentences (e.g., "I see the knives of the cook who..."). For the means end primes, participants again vocally completed the visually presented means end sentences which had an unambiguous completion structure (e.g., "I woke up, took my keys, and..."). These means end sentences were categorized as unambiguous, given that they always encompassed one action (e.g., "I woke up") that was not a preparatory action and thus could not start a means end dependency, and one action (e.g., "took my keys") that could be conceived as a preparatory action for a means end action. When the participants would continue around the non-preparatory action instead of completing the preparatory action (e.g., "I woke up, took my keys, and got dressed"), the prime would be categorized as false (see below). Finally, for the arithmetic prime task, participants were asked to vocally give the solution of the visually presented prime equations. After each prime task, an incomplete but now ambiguous relative clause attachment (50% of trials) or means end (50% of trials) target sentence was presented on the screen. Participants were asked to repeat and complete both types of sentences out loud, and their responses were recorded and categorized after the experiment. Again, to conceal the goal of the experiment, participants were told that "*the sentences are being recorded as stimulus materials to use in later experiments focusing on sentence endings. The music recognition task and math task will be analyzed separately, yet the sentence recording trials are interwoven between music and math tasks to allow for a better differentiation between ongoing and previously heard melodies, and reduce fatigue*". Furthermore, while participants were instructed for the relative clause sentences to "*respond with the first continuation that came to mind*", they were instructed for the means end sentences to "*respond with an action that could follow only one of the previously mentioned actions*".

4.1.5. Analysis

After data collection, the sound recordings (containing the full sentence productions of the participants) were individually rated. Similar to Experiments 1a and b, the structure of these attachments was categorized, and only then was the response added as a variable to the larger data sheet which included the condition and priming structure. Given that all primes were visually presented, or auditorily through headphones, no information was thus available when rating the sentence completion, as to provide a 'blind' rating setting. The native tongue of the rater was Dutch. Relative clause completions were again scored as HA or LA completions based on the number of the relative clause verb. Means end completion trials were scored on their means end relation, and they were discarded if there was (a) no mention of the object used in one of either preparatory actions, and (b) the action in the completion was possible with both objects, or included both objects, and thus impeded an objective classification (e.g., "I open the closet, grab the keys, and put the keys in the closet"). These restrictions applied to both (unambiguous) prime and (ambiguous) target sentences.

A random selection of 10% of the data was reanalyzed by an external rater, resulting in a 92.6% interrater reliability (only 2.2% of the reanalyzed target completions were coded differently, and 5.1% were additional rejections by the external reviewer), which shows the reliability of this standardized categorization approach.

A first analysis was run on the prime task performance of pitch sequence primes. Similarly to the previous experiments, the dependent variable "correct" was related to the independent variables "probe type" (within|between|foil), "prime" (structure of the pitch prime, HA or LA), "Music expertise" (years of formal training), "Music exposure" (time spent listening to music, score 1–5), and "Music interest" (time spent listening to different music, score 1–5). Following the same incremental procedure starting from a random intercepts model, the optimum lmer model included a random slope for probe type (within|between|foil) for subjects. Incrementally testing the significance of the independent variables led to only "prime structure" being incorporated as an independent variable. The results of this model are reported below.

A second analysis was run on the priming results. For this analysis, all primes that were responded to incorrectly were removed. Three independent variables were included in the analysis of target (the structure of the sentence completion, HA or LA): "prime" (the structure of the prime sequence, HA or LA), "prime condition" (the domain of the prime sequence; attachment, means-end, math or pitch), and "target condition" (the domain of the target sequence: attachment or means-end). The optimum lmer model was incrementally determined to be the baseline model with only random intercepts. Following this model, only "prime" and "target condition" were included as independent variables in the best fit model. However, given the strong general effect of "target condition" (i.e., the domain of target sentences, means end or attachment), the dataset was split up into the two domains of target completions. Following the attachment targets only, the best fit was achieved with the standard random-intercepts model including "prime" as an independent variable. Following the means end targets only, the best fit was achieved with a baseline random-intercepts only model including "prime" and "prime condition" as independent variables. Finally, to address the question whether priming (regardless of the differences in significance across domains) was significant in each domain, a standard model was run on each cell across both priming condition and target condition. Finally, a post-hoc analysis was run that tested whether "structure previous target" (the structure of the target completion on the previous trial, see Experiment 1a for inter-trial priming) and "domain prevtarget" (whether the completion on the previous target was made on a relative clause or means end target) significantly contributed to the best fit model of the general analysis. Neither independent variable improved the fit.

All analyses were ran on R (version 3.0.3), using the lme4 package (version lme4_1.1-7). The data files and the R script that was used are freely available on http://opensciencframework.org/profile/v49bp.

4.2. Results

4.2.1. Prime sequence performance

Prime responses were recorded, transcribed, and analyzed. For pitch primes, 66% of the probes were categorized correctly. There was again a difference among the recognition task probes. Whereas 74% of *within* probes were correctly recognized, only 66% of *between* probes were correctly recognized, a marginally significant ($\beta = -0.36$, $z = -1.84$, Pr (>|z|) = 0.06) decrease compared to *within* probes. Participants correctly rejected 58% of the *foil* probes. This decrease in performance to Experiment 1 (78%) can be explained by the use of a more difficult probe task, with foils now having correct pitches but in the wrong order. Upon analyzing the covariates of the musicality questionnaire, we found that the general performance was not attenuated by musical expertise ($\beta = -0.02$, $z = -1.197$, Pr (>|z|) = 0.231) or exposure ($\beta = 0.087$, $z = 1.101$, Pr (>|z|) = 0.271), and also the boundary effect was not attenuated by musical expertise ($\beta = 0.01$, $z = 0.511$, Pr (>|z|) = 0.61) or exposure ($\beta = 0.03$, $z = 0.280$, Pr (>|z|) = 0.780). This was expected given the novelty of the experimental clusters. The fact that we do not find the cluster processing effect to be related to musical expertise, whereas Tan et al. (1981) did find an interaction between their harmonic processing effect and musical expertise, can be explained by the fact that in contrast to Tan et al., our pitch clusters did not correspond to standard chords from tonal harmony.

For the relative clause attachment primes, we first removed the primes (14%) that were not completed in the expected fashion. This loss of attachment priming items was comparable for both priming conditions (46% of retained attachment primes had a high attachment structure). We did the same for means end primes, where 12% of the primes had to be removed for wrongly structured completions. An additional 13% of means end primes were removed based on the rules of (a); not mentioning the object of the preparatory action or (b) not continuing with an action that could only follow the preparatory action, thus not creating a clearly structured prime. Data loss was comparable across priming structures: 45% of retained means end primes had a high attachment structure. For the math primes, 86% of equations were solved correctly. For the mathematical and pitch sequence primes, the prime task response was further incorporated as a factor alongside prime structure and prime domain in the target sequence analyses.

4.2.2. Target sequence performance

Sentence completions were recorded, transcribed, and scored similarly to the first experiment. We removed the trials in which the completions did not meet our standards for objective categorization. 10% of the attachment completions were rejected due to inaudible speech or did not follow a relative clause structure (e.g., "... the chairs of the bar that ... *I saw yesterday*"), and thus were discarded. To code the means end completions, responses were categorized according to their relation to one of the two enabling actions. 15% of the means end completions were rejected due to inaudible speech or did not include a reference to (a) an object of either preparatory action and (b) preparatory-specific action verb, and were thus discarded.

4.2.3. Priming analyses

An overall analysis on the type of target responses by priming domain, priming structure, and target condition, showed that there were significantly ($\beta = -0.45$, $z = -3.426$, Pr (>|z|) = 0.00023) fewer LA responses when completing means end targets (51% LA responses) than relative clause attachment targets (62% LA responses), which is in line with a LA response tendency that has been reported earlier for relative clause attachment priming experiments in Dutch (Loncke et al., 2011). Interestingly, neither the structure of the previous target completion (Pr (>Chisq) = 0.870), nor the domain in which this previous target was construed (Pr (>Chisq) = 0.822) was a significant predictor of the structure of the current trial completion. Furthermore, there was a strong effect of the type of targets on target responses ($\beta = 0.723$, $z = 2.627$, Pr (>|z|) = 0.00036). Therefore, we will discuss the findings separately for both target domains.

In the analysis of the *relative clause attachment* targets, there was a significant priming effect ($\beta = 0.508$, $z = 2.554$, Pr (>|z|) = 0.01), revealing 10% more LA completions after a LA prime. There were no significant interactions between structural priming and the domain of priming (Pr (>Chisq) = 0.559), and neither was there an effect of musical expertise (Pr (>Chisq) = 0.919). The percentage of LA responses in LA and HA prime conditions respectively was 71.16%–59.72% for attachment priming, 67.84%–58.66% for math priming, 71.04%–60.22% for means end priming, and 66.75%–57.46% for music priming. The priming effect therefore, expressed as the difference in proportion of LA responses after LA versus HA priming, is 11% for attachment priming, 11% for means end priming, and 9% for both math and music priming (see Fig. 5).

In the analysis of the *means end* targets, there is a significant priming effect ($\beta = 0.746$, $z = 4.386$, Pr (>|z|) < 0.0001) of means end priming: there were 18% more LA means end completions after an LA means end prime. Interestingly, there were also interactions between prime structure and domain of priming (Pr (>Chisq) = 0.019). The percentage of LA responses in LA and HA prime conditions respectively was 54.65%–45.47% for attachment priming, 52.83%–44.71% for math priming, 58.82%–40.37% for means end priming, and 52.19%–48.61% for music priming. In other words, attachment primes showed a 9% low attachment priming effect, a decrease in priming relative to means end primes that was not significant, but was close to the conventional alpha-value of .05 ($\beta = -0.379$, $z = -1.878$, Pr (>|z|) = 0.06). Similarly, math primes showed an 8% low attachment priming effect, which entails a significant change ($\beta = -0.421$, $z = -2.160$, Pr (>|z|) = 0.03). Finally, the musical primes show only a small 4% attachment priming trend, thereby clearly ($\beta = -0.60$, $z = -3.130$, Pr (>|z|) = 0.002) deviating from the within-domain means end priming. It thus seems that in the case of means end priming, there is some advantage of within-domain priming over across-domain priming (Fig. 6).

None of the analyses reported above showed effects or interactions involving amount of official musical training (reported in years of subscription to a registered musical education). The trial progression (representing whether the trial was early or late in the experiment, indicated by trial number) did not give a significant contribution to the model.

Given the lack of interaction between priming effect and condition, we conducted individual lmer-analyses to indicate the contribution of each prime domain to the general priming effect. When looking at the priming conditions with attachment targets, we found significant priming for every priming condition: attachment primes ($\beta = 0.559$, $z = 3.229$, Pr (>|z|) < 0.002), math primes ($\beta = 0.413$, $z = 2.24$, Pr (>|z|) = 0.025), means end primes ($\beta = 0.452$, $z = 1.858$, Pr (>|z|) = 0.06), and melodic primes ($\beta = 0.386$, $z = 2.279$, Pr (>|z|) = 0.023). When looking at the priming conditions with means end targets, we found no significant musical priming ($\beta = 0.153$, $z = 1.073$, Pr (>|z|) = 0.28). The other

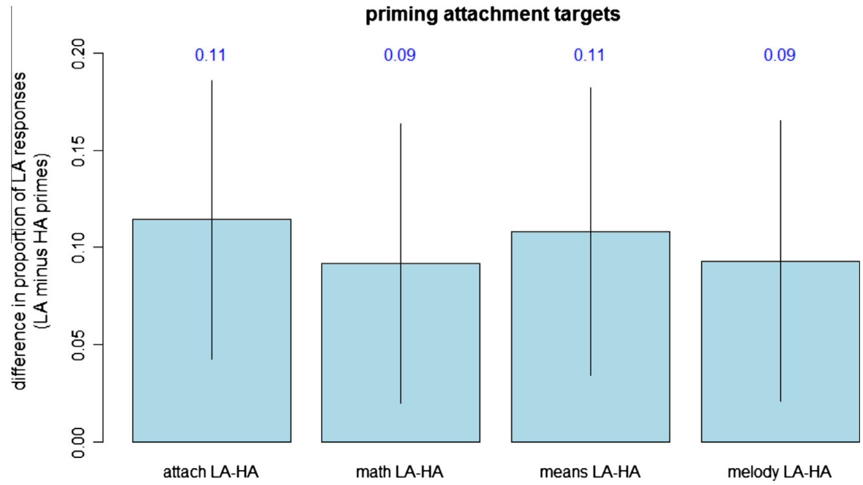

Fig. 5. Priming Analysis Attachment targets Experiment 2. The displayed results are the following difference scores. percentage of LA responses after LA primes minus the percentage of LA responses after HA primes. The priming effects are jointly presented with their respective confidence intervals. The confidence intervals were derived from linear mixed models with crossed random effects (see text).

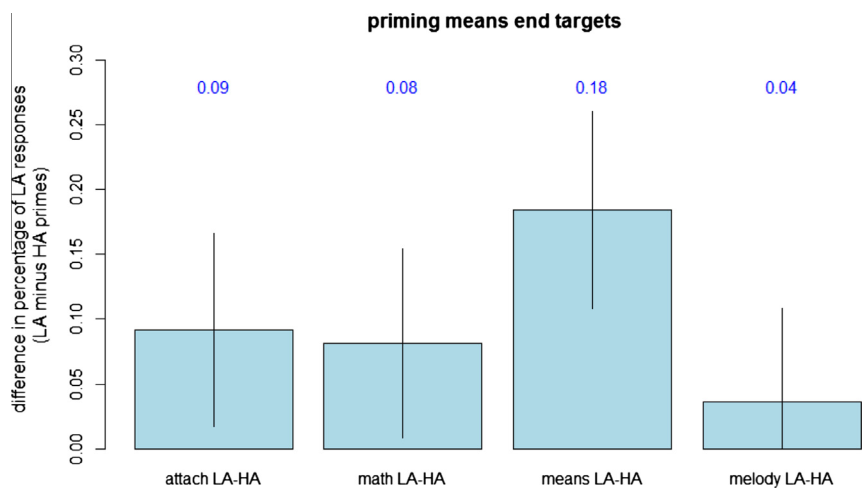

Fig. 6. Priming Analysis Means End targets Experiment 2. The displayed results are the following difference scores: amount of LA responses after LA primes minus the amount of LA responses after HA primes. The priming effects are jointly presented with their respective confidence intervals. The confidence intervals were derived from linear mixed models with crossed random effects (see text).

conditions did show significant priming effects: attachment primes ($\beta = 0.3647$, $z = 2.105$, Pr ($>|z|$) = 0.0353), math primes ($\beta = 0.316$, $z = 2.187$, Pr ($>|z|$) = 0.029), and a large effect for means end primes ($\beta = 0.826$, $z = 5.483$, Pr ($>|z|$) < 0.00001).

4.3. Discussion

Experiment 2 provided a replication of the cross-domain (music to language) priming effect found in Experiment 1a, and furthermore broadened these effects across priming and target domains. Apart from prime structures in the musical domain, prime structures in the domains of math (cfr. Scheepers et al., 2011) and action description (cfr. Allen et al., 2010) significantly influenced the preferred attachment choice in relative clause completion. Furthermore, these within-domain and cross-domain attachment priming effects were similar for all priming conditions. Additionally, the four priming domains (math, music, relative clause attachment, and means end completion) also primed structural choices concerning means end completion in action description (though musical primes did not reach significance and some differences between priming conditions were observed). In general, the Experiment 2 thus confirmed the possibility for cross-domain priming of structural information processing.

5. General discussion

Behavioral and neuroimaging studies on structural processing of musical and linguistic sequences have argued for both overlap and for domain-specificity. The SSIRH (Patel, 2003) reconciles such seemingly conflicting findings by arguing that syntactic processing in each domain uses domain-specific representations, but that the resources fueling the structural processing mechanisms (e.g., dependency processing) overlap between both domains. The reported experiments aspired to provide evidence in favor of shared structural processing by showing direct priming from attachment choices in one domain to another domain, which could then be interpreted as priming of dependency structures. Experiment 1a showed that the attachment of a relative clause to a main sentence could be primed by pitch sequences with a similar structure, thus providing the first evidence for priming from music to language. In a control experiment (Experiment 1b) we replaced the pitch sequences with simple color sequences that had the identical grouping to the pitch sequences, but no dependency structure. In such stimuli, this priming effect could not be replicated. Experiment 2 replicated the music-to-language priming effect, but importantly, generalized it to primes that contained different forms of structural rules: arithmetic equations, relative clause sentences, and sentences with a means end parsing. There was no consistent evidence that priming was stronger within-domains than between-domains. However, this is a feature to be further explored, and can possibly be related to the similar finding that there is mixed evidence with respect to whether structural priming within-languages is stronger than between-languages (Cai, Pickering, Yan, & Branigan, 2011; Fleischer, Pickering, & Mclean, 2012; Schoonbaert, Hartsuiker, & Pickering, 2007).

We observed cross-domain priming despite considerable differences between domains such as acquisition process and effort. Whereas the musical clustering rules can be regarded as implicitly acquired structural rule representations, the math equation primes require the use of formally instructed rules. Furthermore, the math equation prime task might arguably ask for more elaborate processing than the melodic pitch recognition task. However, these apparent differences did not seem to result in differences in priming on the relative clause completion task. Furthermore, though the means end structures are presented and responded to linguistically, it must be noted that the type of sentential structure (being based on thematic action) was strongly different from the attachment structures. Therefore, a question for future research could be: "to what extent one can find similar priming effects with means-end stimuli created in a visual or spatial domain?". In summary, though it is still too early to define the characteristics and the limitations of the current cross-domain priming effects, the wide variety of priming structures used in this experiment seems to suggest that the attachment processes shared across domains have a wide scope. Our most important result is that there is overlap in some of the mechanisms used to structure sequences of symbols in music, sentence processing, math, and linguistic structures describing actions.

As reported in the introduction, these findings of overlap contribute to a larger body of evidence in favor of models suggesting domain-general syntactic working memory resources involved in dependency processing (cfr. DLT, Gibson, 2000, SSIRH, Patel, 2003; SWM, Kljajevic, 2010; Fiveash & Pammer, 2012). It remains important to address that though the idea of dependency processing as a common ground between language and music (cfr. SWM, Kljajevic, 2010; SSIRH Patel, 2003) has been incorporated in many studies using interference paradigms (e.g., Fiveash & Pammer, 2012), this is not the case for the structural priming evidence we have based ourselves on in the abovementioned experiments. More specifically, previous findings of cross-domain structural priming (Scheepers et al., 2011; Scheepers & Sturt, 2014) seem to support a more "representational" account in which it is the complexity of the attachment host which differentiates HA and LA sequences. However, unlike Scheepers et al.'s mathematical equations, the structure of pitch sequences typically has a somewhat less stringent representational pattern, as it is often influenced by a variety of factors (such as tension, rhythm, and cadence). Furthermore, we reasoned that, since our cross-domain priming effects included the priming of an experimentally manipulated pitch dependency structure (i.e., simple grouping patterns rather than explicit rules), as well as a loose non-syntactic action structure (cfr. means end sentences), our experiments did not warrant a similar "representational" interpretation as Scheepers et al. In this line, it is important to note that in psycholinguistics, the idea of dependency processing mechanisms as an explanation for structural priming effects has previously been used (Desmet & Declercq, 2006; Loncke et al., 2011). More specifically, short-distance dependency processing (e.g., a low attachment structure) might be more likely when the same principle was applied in the structural processing of preceding sequences. Following the recent evidence (e.g., Kljajevic, 2010) in favor of a domain-general dependency processing (see Section 1), we thus suggest that the found cross-domain priming effects can, similarly to earlier linguistic priming effects, be explained through priming of domain-general dependency processing mechanisms.

Regardless of the discussion concerning the difference in within versus between domain priming, and the further exploration of the cognitive and neurophysiological basis of structural integration mechanisms, the main contribution of the current paper is that there *is* evidence in favor of the claim that the overlap between domains of music and language (and possibly other domains of structural processing) which extends beyond interference in shared processing.

6. Conclusion

Previous research has consistently provided suggestive evidence in favor of an overlap in structural processing across domains (e.g., Fedorenko et al., 2009; Koelsch et al., 2005; Slevc et al., 2009), mainly through findings of interference in integrational resources during joint tasks (cfr. Fiveash & Pammer, 2012). To investigate cross-domain influences on more "default" processing, we applied the paradigm of structural attachment priming (Scheepers, 2003; Scheepers et al., 2011; Scheepers & Sturt, 2014), investigating cross-domain influences on sequential structural processing. Our experiments found clear evidence for our hypotheses. First, structural priming occurs between a non-linguistic auditory prime and a linguistic structural target completion. Importantly, a control experiment was run in which the primes contained identically chunked primes with no dependency structure, and no such priming was found. Second, these cross-domain priming effects can be broadened to other domains, including math and action-based linguistic structure. These results have several implications. First, they clearly indicate overlap in structural processing mechanisms across linguistic and non-linguistic auditory processing, thus providing evidence in favor of a shared pool of dependency processing resources (SSIRH, Patel, 2003). Second, the results suggest a broadening of the theoretical interpretation of previously found cross-domain priming effects (Scheepers et al., 2011; Scheepers & Sturt, 2014) insofar as that not only an abstract representation of hierarchical complexity, but rather a dependency-based processing of both syntactic and non-syntactic structure can be the basis of structural priming. Such findings of structural persistence across several domains of dependency processing certainly warrant a critical approach to our classically domain-specific models of syntactic processing. Overall, we think that these findings provide us with a different perspective to look at both the general structuring capabilities our cognitive system supports, and the specificity of the processing mechanisms involved.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2015.09.013.

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