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FACULTEIT PSYCHOLOGIE EN
PEDAGOGISCHE WETENSCHAPPEN

SYNTAX ACROSS DOMAINS:

OVERLAP IN GLOBAL AND LOCAL STRUCTURE PROCESSING

Joris Van de Cavey

Promotor: Prof. Dr. Robert J. Hartsuiker

Proefschrift ingediend tot het behalen van de academische graad
van Doctor in de Psychologie

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‘ I may not have gone where I intended to go,
but I think I ended up where I needed to be’

– Douglas Adams

Looking back at the past four years, one word that comes to mind is ‘serendipity’. It has been an interesting journey, and a circuitous one. We started the project with the goal to provide a novel perspective on joint processing studies in their claim for a domain-general pool of structural processing resources. Faced with the development of a novel structural processing measure, we attempted to tackle the creation of experimental structure in simple pitch sequences. This sparked our interest in how pitch sequence structures might be developed to match the structure of naturalistic sentences. This side question rapidly developed into a main focus of the dissertation, and since then, a whole array of fortuitous finds in the literature paved the way for the research that we can now report. Eventually, we were able to provide evidence for interactions in structural processing which were not limited to experimental joint processing conditions, but could be generalized to more naturalistic conditions as well.

When regarding the end result of these four years of meandering research, I have a lot of gratitude for my supervisor, **Rob Hartsuiker**. Working under your guidance has been a wonderful experience. I am very thankful for your support and enthusiasm, without which this project would not even have come into existence. And of course, I greatly admire your knowledge and insight, which has definitely helped me find my way out of some exasperating problems. What I am most grateful for however, is your exemplary scientific mind set. Since most of the people reading this dissertation have personal experience with a PhD, I don't need to explain that publication pressure can level a near existential *Angst* in a graduate student's life. Nevertheless, you always guided me back to the core of what I like so much about research: the thrill of developing and exploring novel paradigms, the elegance of models, the 'how and why' of our cognitive functioning, the belief in good science practice. Moreover, I have been able to spend four years doing things I intrinsically love doing, and that is mostly due to how considerate you are to the people you work with and their interests.

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CHAPTER 1
INTRODUCTION

The current dissertation is aimed at providing novel perspectives on the study of structural processing in the human mind. Why is the study of structural processing valuable to our understanding of human thinking? In order to provide an answer, let us consider a broader question: what sets our human cognition apart from that of other animals?

Answers on the latter question would immediately point to our cognitive capacity: we are (arguably) smarter than most other life forms on this planet. How did we develop such an intellect? Traditionally, our intelligence has mostly been related to tool use: learning how to make and manipulate useful objects requires quite some thinking. But something doesn't fit well with this picture: the evolutionary expansion of our brains started hundreds of thousands of years before the use of tools. Then what has driven our intellect forward throughout our evolution? The answer might be quite simple: we are a thoroughly social species, and social behaviour, especially communication, is something that has formed and boosted our cognitive capacities throughout prehistoric and historic times (Gintis, 2014).

In this sense, communication cannot be circumvented when talking about what makes us human. Our capacity for language processing is seen as a hallmark of human cognition. Of course, several other social species have also developed certain forms of communication. What is the difference between animal communication and human language? A first idea might be the level of semantics: that whereas humans can use calls which relate to a specific concept (e.g., *'dog'*), animals only have non-semantic calls (e.g., barking) to communicate with. This myth has been somewhat debunked over the past decades (Manser, 2013). Seyfarth, Cheney and Marler (1980) have for example reported semantic communication in vervet monkeys, which seem to have different calls for different kinds of danger (*'snake'*, *'leopard'*, *'eagle'*). Here, one might argue that such different calls are just functional references (i.e., a call that has been developed for a specific situation, but which does not implicate an understanding of what is being said). However, studies on primates have shown that bonobo monkeys for example are able to combine the 'words' (usually developed in a sort of sign language) for *water* and *bird* when asked to describe a duck (Savage-Rumbaugh & Lewin, 1994). So, what aspect of language then makes us unique as humans among other species?

At this point, our capacity for structural processing comes in to play. One aspect that makes human language so powerful, is that we are able to combine meaningful semantic elements in such a way that we can convey and interpret something about the relationship between those elements. For example, in the sentence *'the dog is biting the snake'*, it is not only conveyed that there is a dog and a snake, but also which animal is being attacked. The function of structural processing has been extensively studied in psycholinguistics, given its importance in understanding how our language system works. We would not be able to understand sentences if we were not able to process the syntactic relationships between the words that are presented (e.g., that *'dog'* is the subject of the verb *'chases'* in the sentence *'the dog chases the rabbit'*).

Although structural processing (unsurprisingly) receives much attention in linguistic research, it is also required for the production and comprehension of non-linguistic materials. To illustrate the idea of structural processing in non-linguistic materials, let us compare listening to sentences with listening to music. At first glance, one might say that structural processing only applies to the linguistic materials. After all, it is quite clear that understanding sentences depends on accurately processing how the words in that sentence relate to each other (i.e., structural processing). As far as listening to music is concerned, the idea of processing structure among tones in melodies might seem somewhat vague. Nevertheless, when a wrong chord is played in a melody, most people will find it very easy to detect this. Not necessarily because the chord in itself is wrong (in other melodies it might sound good), but because it does not fit in with what has been played before. This shows that, on a more implicit level perhaps, processing the relationships between elements is also of strong importance in non-linguistic domains like music. To give another illustration, let us compare the comprehension of written sentences (e.g., *'I see the lights of the room that are bright')* and written arithmetic equations (e.g., *'3 + (2 + 2) x 5'*). The content of these two sorts of information is completely different. Nevertheless, the comprehension of both requires structural processing (Scheepers, Sturt, Martin, Myachykov, Teevan, & Viskupova, 2011). An accurate understanding of sentences as well as mathematical equations is impossible without integrating the separate elements along certain rules (syntax, bracket hierarchies). To conclude, structural processing is mostly studied with regards to linguistic information, but is also important in the processing of several forms of non-linguistic information. The idea that structural processing applies to several content domains (sentences, music, arithmetic equations) might therefore be important in modelling exactly how structural processing works.

In the following segment, we will shortly discuss how structural processing as a cognitive function is currently modelled, which entails the idea that structural processing is specialized across several domains (language, music, action). In the subsequent segments, we will discuss how parallels in the modelling of structural processing can be found across linguistic and non-linguistic domains, and to which extent research supports the idea of domain-generality in structural processing. In a final segment, we will discuss how theories have attempted to model this domain-generality in structural processing, the research which supports those theories, and the limitations that domain-general approaches to structural processing have.

On the basis of this introduction, we will then report studies that focus on (a) addressing current limitations in research supporting the idea of domain-generality, and (b) investigating to what extent interactions in structural processing across domains can be observed in more ecologically valid paradigms. The implications of these studies will be discussed at length in a discussion chapter. For now, let us start by sketching how structural processing is modelled in cognitive science.

Structural Processing as a Cognitive Function.

How do we start describing structural processing as a cognitive function? It might be important to first state exactly what we mean by a ‘cognitive function’. In cognitive science, it is generally agreed upon that our brain responds differently to different kinds of information. Our cognitive capacity can be subdivided into several smaller ‘cognitive functions’, modules which are specialized in processing specific sorts of information: a visual centre, an auditory centre, a specific region for recognizing faces, and so on. This idea of cognitive modularity has become hugely popularized with the publishing of the book ‘Modularity of Mind’ by Fodor (1983). Over the past decades, it has been strongly debated what exactly counts as a ‘cognitive module’ (e.g., Sperber, 2005), but the idea of our mind being governed by a combination of specialized cognitive functions has been well-embedded in cognitive psychology. There are several indications for a modular approach to human cognition. A subdivision of our general cognitive capacity into smaller modules make sense from an evolutionary standpoint (different senses, like seeing and hearing, being represented somewhat separately in the brain). Furthermore, cognitive modularity is often (e.g., Barrett & Kurzban, 2006) deemed necessary to account for the capacity we have to process highly complex information, like language (which is then assumed to be tackled by a collection of specialized functions that share the work load).

Following the idea that our cognitive capacity is supported by a combination of ‘cognitive functions’ that are specialized in processing certain types of information (Barrett & Kurzban, 2006), a cognitive function can be described on the basis of the type of information in which it is specialized. Which leads us to the question: if we look at structural processing as a cognitive function, what type of information is structural processing specialized in?

Structural Processing: Types of Information

Structural processing can be seen as a specialized processing of a certain type of information, namely sequentially provided elements which stand in a meaningful relationship to each other. This has been discussed in the previous parts of the introduction. But furthermore, most models on structural processing also suggest a specialized processing of information following content domains. Structural processing is modelled as a specialized processing of linguistic information in language syntax theories, as a specialized processing of tonal information in harmonic music theories, and so on.

Where does this assumption of specialized structural processing along content domains stem from? It mainly originates from the general belief (cognitive science included) that we process stimuli differentially on the basis of their meaning (i.e., language, music, and math), rather than on the formal properties of the input we receive (i.e., visual or auditory, simultaneous or sequential). However, as Barrett and Kurzban (2006) note, modelling information processing in terms of the meaning of information might not make much sense – after all, our neurons do not know the 'meaning' of the input they are processing. Furthermore, though structural processing is largely modelled as domain-specific, general definitions of structural processing seem to apply across domains (Patel, 2008). Across content domains, structural processing is assumed to be a cognitive function specialized in the same sort of information, namely information that contains a combination of discrete structural elements following a certain set of principles (sentences as a combination of words following syntax, melodies as a combination of tones following tonal harmony, math equations as a combination of symbols following explicit rules such as bracket hierarchies).

In sum, there seems to be somewhat of a discord in the way structural processing is conceptualized in current cognitive research. One the one hand, cognitive research largely models structural processing as a cognitive function that is specific to a content domain, with syntactic processing of language being the main focus. On the other hand, a functional specialisation of a cognitive function along the lines of 'meaning' of information might make little sense from a neurological perspective, and that structural processing can also be more generally defined across content domains. To further elaborate upon a domain-general perspective on structural processing, we will now turn to a comparison of how structural processing is conceptualized within linguistic and non-linguistic domains.

STRUCTURAL PROCESSING: CONCEPTS ACROSS CONTENT DOMAINS

Structural Processing in Language.

Dependency Processing. When studying the structural processing of linguistic information, several theories assume that two important processes must take place. One is that the already processed sentential structure must be maintained in memory, and the other is that novel elements then need to be integrated into this structure (Gibson, 1998). To achieve such integration, it is important to keep track of the incomplete dependencies in the sentence which have been encountered thus far.

What is meant by this? For example, consider the sentence *'The journalist who the newscaster sent to the politician recorded a great speech'* as compared to the sentence *'The journalist who sent the newscaster to the politician recorded a great speech'*. Most people will agree that the first sentence is more difficult to understand. This is not due to the words being used (as they are the same) or the ambiguity of the sentences (as both sentences can only be interpreted in one way). Then what causes the difference in sentential complexity? This can be related to the fact that in the sentence

‘The journalist who the newscaster sent to the politician recorded a great speech’, the relative pronoun *‘who’* is in the subject position of the relative clause, but in the object position of the main clause. It has been shown that object-extracted relative clauses are processed with more difficulty as compared to subject-extracted relative clauses (e.g., King & Just, 1991).

One of the main theories explaining the abovementioned difference in object-extracted versus subject-extracted relative clauses is related to incomplete dependency processing (see Gibson, 2000). The structural processing of the verb *‘sent’* in the sentence *‘The journalist who sent the newscaster to the politician recorded a great speech’*, can be described in the following steps: *‘sent’* must be stated as a new discourse referent, and *‘who’* must subsequently be integrated into the subject position of this verb. This integration between *‘who’* and *‘sent’* is not separated by new discourse referents, and hence does not require effortful processing. The processing of the verb *‘sent’* in the sentence *‘The journalist who the newscaster sent to the politician recorded a great speech’* however is more complex. The verb *‘sent’* is again a new discourse referent, and the integration of *‘the newscaster’* as the subject of this verb is again not separated by discourse referents. However, in the latter sentence, the NP *‘who’* must be indexed as the object position of *‘sent’*, and this integration is separated by two novel discourse referents, namely *‘the politician’* and *‘sent’* (for an extended description, see Gibson, 2000).

Such examples suggest that structural processing complexity is related to (working memory) resources involved in keeping incomplete dependencies in memory, and the distance between the elements which are to be integrated. This idea has been developed in the ‘Dependency Locality Theory’ (DLT), as reported in several influential papers by Gibson (1998, 2000). The DLT states that more resources will be required when performing integrations between an incomplete dependency and a novel element if the two are separated by a larger number of other discourse elements. Much of the differences observed when studying the structural processing of clause attachments in sentences (‘He watches *the teachers* of the school *who* are tall’ as compared to ‘He watches the teachers of *the school that* is quiet’) are related to this idea of dependency processing. The distance between a noun phrase and its referent strongly determines the resources required for structural integration (Garrod & Sanford, 1994; Gibson, 2000; Grodner & Gibson, 2005).

Expectation-Based Syntactic Comprehension. Of course, the idea of on-line dependency processing is only one of the many mechanisms by which structural processing in language has been described. Another influential account for structural processing in language suggests that linguistic comprehension occurs through the creation of (structural) expectations. This idea has been thoroughly described in several so-called ‘constraint-satisfaction’ models, focusing on linguistic probabilities (MacDonald, 1993; Jurafsky, 1996). Following these models, people will make predictions about upcoming elements in sentences by evaluating the probability of several structural alternatives in parallel (Jurafsky, 1996).

For example, consider the sentence ‘The *horse raced past the barn fell’*. The accurate interpretation of this sentence would be the same as *‘The horse, (that was) raced past the barn, fell’*, yet this is often not the initial reading of the sentence. Participants initially interpret the verb *‘raced’* as the main verb (i.e., *‘The horse raced past the barn’*), which leads to an unexpectancy effect when encountering the verb *‘fell’*, as it indicates that the previous reading of the sentence was wrong. This type of sentence is called a ‘garden path’ sentence in psycholinguistics, given that it incites readers to adopt a wrong initial reading.

Of course, incremental processing theories such as the DLT (Gibson, 2000) are valuable in interpreting ‘garden path’ sentences. Following the idea of memory-constrained incremental dependency processing, it is logical that the syntactically complex (e.g., *‘the horse’* being placed in the object position of *‘raced’*) analysis of new input is dispreferred. As ‘constraint-satisfaction’ models state, prior exposure to linguistic input might play a role here, too. The probability of the verb ‘raced’ constituting the main phrase (i.e., *‘the horse raced past the barn’*) is much higher than that of the verb *‘raced’* constituting a passive relative clause (e.g., *'the horse (that was) raced past the barn fell'*). Furthermore, the incomplete dependencies which are encountered (e.g., *'the horse'*) also provide some information about what is to be expected (e.g., when encountering *'horse'*, the verb *'raced'* fits very well with *'horse'* as the subject). In other words, structure processing difficulties (like the 'garden path' example mentioned above) can also be related to structural probabilities and participant's expectations. Importantly, processing difficulties can then arise when resources are not efficiently allocated along the different possibilities, and must be reallocated. In other words, following 'constraint-satisfaction' models as well, encountering structural complexities will thus incite a more effortful processing.

Over the past decade, several studies (e.g., Konieczny, 2000; Hale, 2001; Levy, 2008) have addressed and compared so-called 'resource-requirement' (e.g., DLT, Gibson, 2000) and 'constraint-satisfaction' (e.g., Jurafsky, 1996) models in the framing of structural processing complexity. What we would like to retain for the current dissertation, is that structural processing in linguistic research is linked to the idea of dependency processing and structural expectancy generation, and that both accounts suggest that encountering structural complexities involves a higher demand on structural processing resources.

Structural Processing in Non-Linguistic Materials

The study of Non-Linguistic Materials. The research on structural processing discussed thus far has been oriented towards linguistic materials. Nevertheless, as we have mentioned earlier, structural processing is also of high importance for non-linguistic materials, like music for example (Rohrmeier, 2011). There seem to be somewhat different perspectives on the study of language and music, however. Linguistic processing is often studied as a universal human capacity, whereas music, both in general thought as well as in cognitive research, has often been regarded as an acquired skill (instrumental music production and formal music theory). Such a focus on expertise might overshadow the fact that, as has been mentioned earlier, there are also several universal musical capacities that people have, regardless of formal training. A person does not need formal musical training to hum a melody, or to enjoy a suspenseful theme in a movie. When it comes down to perceiving music in daily life, most of us have a high capacity for applying (mostly subconsciously acquired) harmonic rules to incoming sounds. If we would not have acquired the harmonic regularities following which melodies are composed, we would not be able to enjoy music as much more than a random sequence of sounds. From these short examples, it becomes clear that the questions cognitive science faces when investigating structural processing in language, also resurface when studying structural processing in non-linguistic domains: how do we acquire structural rules (musical harmony, linguistic syntax), and how do we apply these combinatory rules to create and interpret meaning from a sequential combination of elements (melodies, sentences)?

Interestingly, such questions often prove hard to answer for language, given the high complexity of linguistic materials on several levels (semantics, thematic structure, syntactic structure, and so on). Such semantic references are however not present in domains like music, making such domains very interesting for more direct approaches in structural processing research (Lerdahl, 2001; Patel, 2008; Winograd, 1968). After all, music might not have the referential components which are present in language (like the semantic meaning of words), but it still is a highly structured form of sequential information (Budge, 1943; Krumhansl & Jusczyk, 1990; Tillmann, Bharucha & Bigand, 2000).

In sum, the study of structural processing in non-linguistic domains is not only possible, but might in fact give a valuable perspective on structural processing in language. To illustrate this point, the following segments will discuss how the two theories on linguistic structural processing that were mentioned earlier (dependency processing and expectation-based comprehension) relate to the study of structural processing in a non-linguistic domain such as music.

Structural Processing in Non-Linguistic Materials. Before we address the concepts of dependency processing and expectation-based comprehension in music, it might be important to give a general idea of how tonal harmony relates to linguistic syntax. This can be done by comparing how sentences (Generative Grammar, Chomsky, 1965) and melodies (Generative Theory of Tonal Music, GTTM, Lerdahl & Jackendoff, 1983) can be studied as integrational structures.

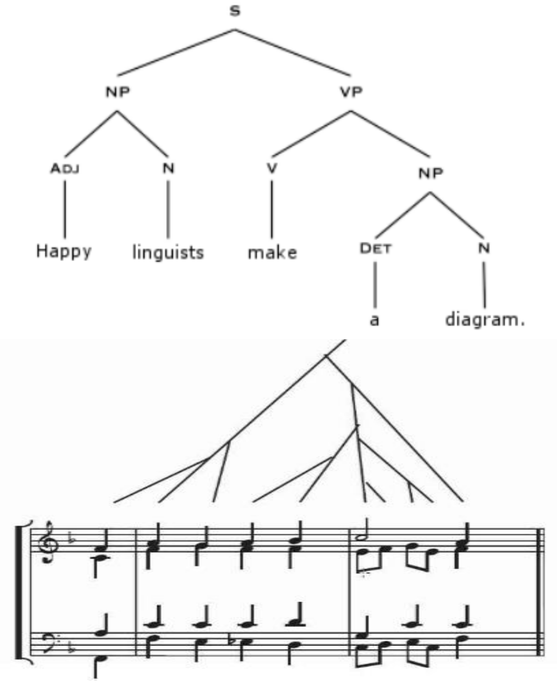

Figure 1: Integrational structures in language and music

In language, the idea of having integrational structures in sentences is quite well-known, as it is formally taught throughout our education. Sentences can be represented along tree structures, which indicate how the words presented in the sentence structurally relate to one another following syntactic regularities (e.g., given that *'happy'* is an adjective relating to the noun *'linguist'*, the two words can be summarized as one noun phrase; upper panel of Figure 1). As shown in the lower panel of Figure 1, melodies can also be represented in a tree structure. Importantly however, musical theory does not entail the hierarchical combination of elements based on stringent syntactic rules, as in language. Rather, 'subordinate' tones can be related to more central tones in the sense that they are elaborations of these central tones. When listening to a chord sequence for example, certain chords can be 'reduced' to one more central chord (e.g., a 'Sonata in C Major' is a musical piece that can be seen as series of eloquent elaborations of on the basis of one central chord).

Therefore, whereas sentences can be studied following their integrational structure on the basis of hierarchical combinations (e.g., 'adjective' and 'noun' can be combined on a higher level to 'noun phrase'), musical materials such as chord sequences can be studied following their prolongational reduction (GTTM, Lerdahl & Jackendoff, 1983). This way, both materials can be represented as tree structures (Figure 1), and the idea of 'dependencies' and 'structural expectancies' can be compared across linguistic and musical structure.

Dependency Processing in Non-Linguistic Materials. Interestingly, when studying structural processing of music (for example, in the GTTM model, Lerdahl & Jackendoff, 1983), there is an important role for what is described as the Tonal Pitch Space (TPS, Lerdahl, 2001) theory. This theory states that the 'prolongational reduction' mentioned earlier is influenced by the distance between elements. As the idea of prolongational reduction is that a sound can be 'reduced' as a (modified) repetition of a previous harmonic element, the harmonic distance between this component and its reference point determines the instability of the component. In other words, the instability of an incoming event is measurable by the distance in the prolongational reduction tree from a global tonic (for a more elaborate view, see Lerdahl & Krumhansl, 2007). The TPS thus has a similarity with the Dependency Locality Theory in language (DLT, Gibson, 2000), which states that the resources required for integrating a word in a sentence is dependent on the distance between the incomplete dependencies and its governor. The idea of the TPS tension component has been paramount to the interpretation of harmonic processing effects in several studies (Krumhansl, 1996; Lerdahl & Krumhansl, 2007).

Expectation-Based Comprehension in Non-Linguistic Materials. In music cognition, the idea of harmonic processing through the creation of structural expectancies is also generally accepted (e.g., Wiggins, 2011). Importantly, such expectancies are not simply generated on the basis of the immediately preceding context, but are also determined by the global harmonic structure of the melody (Koelsch, Rohrmeier, Torrecuso & Jentschke, 2013; Byros, 2009). The probability profiles of harmonic expectancies are strongly based on the long-distance dependencies (and harmonic instability, as discussed in the TPS) that are encountered. Computational models (Wiggins, 2011) have shown that harmonic expectations can be brought back to a probability ranking of structural possibilities, similarly to what has been argued for language by ‘constraint-satisfaction’ models (see Jurafsky, 1996). Furthermore, the ecological validity of such models has repeatedly been shown by linking computational models to patterns in neurophysiological data (Pearce, Ruiz, Kapasi, Wiggins, & Bhattacharya, 2010).

In summary, when comparing conceptualisations of structural processing in linguistic and non-linguistic domains (dependency processing, expectation-based processing), strong parallels can be found. In the next segment, we address how such similarities in the theoretical modelling of structural processing across content domains relate to parallels in structural processing research conducted across content domains.

STRUCTURAL PROCESSING: PARALLELS ACROSS CONTENT DOMAINS

Evolutionary Perspectives on Structural Processing. When studying the evolutionary origins of structural processing, it is often assumed that the language faculty might piggyback on the neural networks that were already established for the processing of action. The structural processing of actions is often said to serve as an evolutionary basis for structural processing in both language and music (Fitch & Martins, 2014). Furthermore, the evolutionary commonalities between the processing of music and language have been generally accepted and extensively discussed (Brown, 1999; Cross, 2011).

Implicit Learning. The process of implicit learning is a key element in several domains of cognitive science (Dienes, 2011; Perruchet, 2008). Implicit learning can generally be defined as the unconscious acquisition of knowledge. For example, think about a popular theme on the radio that you cannot seem to get out of your head. Most likely, you did not explicitly study the melody, but by means of listening to it repeatedly, you have unconsciously memorized it. This is called ‘implicit sequence learning’, which also drives the acquisition of language in early infancy. Long before children learn to read or write, they can understand and form meaningful sentences, since they have implicitly acquired the meaning of words and the syntactic rules by which those words are structured, simply by repeatedly being exposed to language in their early lives (Reber, 1993).

It is interesting that the idea of implicit learning also holds for non-linguistic content domains, such as music. Music processing largely depends on the rapid, exposure-driven acquisition of harmonic structure. For example, as mentioned earlier, formal musical training is not necessary to detect when someone plays the wrong chord in a melody. In fact, music has been quite an intensively studied domain in terms of implicit learning (Pearce & Wiggins, 2012; Rohrmeier, 2010).

Developmental Perspectives. As has been suggested by the comparison of implicit learning in language and music, there are also some strong similarities in developmental perspectives on structural processing in language and music. Learning in both domains is deeply entangled in early life. This becomes apparent when we look at the similarities in the time span which marks the development of structural processing capacities in language and music. The competence of both native musical harmony (Corrigal & Trainor, 2010) and native language syntax (Höhle, Weissenborn, Schmitz, & Ischebeck, 2010) can already be detected in infancy (2 to 4 years of age). Around this time, children are able to detect phrase structure violations in sentences (Oberecker, Friedrich, & Friederici, 2005) as well as the presentation of harmonically incongruent chords in melodies (Corrigal & Trainor, 2010). A mastery of the culture's language (Nunez et al., 2011; Scott, 2004) and music (Corrigal & Trainor, 2010) develops over early childhood (5-6 years of age), with 'adult' levels in the processing of complex sentences (Friederici, 1983) and pitch discrimination (Werner & Marean, 1996) being typically achieved around 10 years of age. For a more elaborate overview of the similarity in the development of linguistic and musical capacities, see Brandt, Gebrian and Slevc (2012). Overall, we can state that the acquisition of musical and linguistic competences in structural processing is strongly intertwined.

The idea that structural processing competences develop similarly over linguistic and non-linguistic domains, leads to the question whether interactions can be found in the development of structural processing capabilities across domains. In fact, this does seem to be the case. It has repeatedly been shown that children taking music lessons also show linguistic enhancements as compared to their non-musician peers. For example, in an EEG study considering the effects of music on child development, Jentschke and Koelsch (2009) have found that musically taught children do not only show an increased eRAN amplitude ('early right anterior negativity', which is related to a greater sensitivity for violations of musical harmony), but also that there was a more strongly developed eLAN ('early left anterior negativity', related to violations of linguistic syntax) as compared to children who did not receive musical training. Furthermore, it has been shown (Jentschke, Koelsch, Sallat, & Friederici, 2008) that children with syntax processing difficulties in language tend to also have more problems with processing musical stimuli. Another example is the study of Anvari, Trainor, Woodside, and Levy (2002). In this study, it was found that musical capacities are strongly related to early reading skills in children. These studies suggest that structural processing capacities for musical materials might directly interact with capacities required for the structural integration of sentences.

Neural Overlap. Given the similarities between structural processing across domains that we have discussed from both an evolutionary as well as a developmental perspective, it seems plausible that also in neurological studies, some parallels might be found.

It is important to note that some evidence exists in favour of double dissociations between the processing of language and music. More specifically, the study of amusia seems to suggest the existence of brain networks that are specialized for music cognition (Peretz & Coltheart, 2003). Deficits in such music-specific brain regions do not seem to affect language processing. Amusics have great difficulties when it comes to pitch processing, though their language processing is not impaired (Ayotte, Peretz & Hyde, 2002; Peretz, 2006). For a review on amusia, see Alossa and Castelli (2009). Furthermore, it has been also shown that preserved musical processing can be found in people with linguistic deficits (Luria, Tsvetkova, & Futer, 1965; Tzortzis, Goldblum, Dang, Forette, & Boller, 2000). These studies on patient populations thus suggest that brain networks can be specialized for structural processing in music as opposed to language. Also in non-patient populations, it must be noted that language-specific and music-specific regions can be disseminated (Fedorenko, Behr, & Kanwisher, 2011; Fedorenko, McDermott, Norman-Haignere, & Kanwisher, 2012). Fedorenko et al. (2011) found a series of language-sensitive brain regions (by contrasting the reading of sentences to lists of pronounceable non-words), which could be disseminated from more domain-general processing (e.g., working memory, math, cognitive control, music, …). In a subsequent study, Fedorenko et al. (2012) found temporal regions to be involved in musical processing (by contrasting musical clips to pitch-scrambled and rhythm-scrambled versions of those same clips) yet not high-level linguistic processing. This recent evidence thus suggests that largely separable neural sources are implied in the structural processing of music and language.

This being said, it should be noted that finding separated neural regions for the structural processing of linguistic and non-linguistic materials does not exclude that such domain-specific regions might actively interact with more domain-general regions. In fact, several findings have argued against a fully dissociated structural processing of linguistic and musical materials. For example, Patel, Iversen, and Hagoort (2004) investigated the effects of harmonic priming on people with a linguistic syntax comprehension deficit. They studied Broca's aphasics on their ability to process chords, and found that participants did not show harmonic expectancy effects (i.e. processing target chords faster when they are harmonically closer to the preceding context). This can be taken as evidence that processing of 'musical syntax' might be dependent on brain regions which are also involved in the structural processing of language. Also in non-patient populations, several studies investigating the structural processing of language and music find overlapping neural regions and electrophysiological components. One example is the study of Patel, Gibson, Ratner, Besson, and Holcomb (1998), who found no discernible distinction between the P600 event-related potential when elicited through structural expectancies in language or music. Furthermore, neuroimaging research seems to find overlapping regions that are related to structural processing across domains (Maess, Koelsch, Gunter, & Friederici, 2001; Sammler et al., 2013). Of course, one must be cautious in interpreting findings of neural overlap, with regards to possible averaging effects (see Nieto-Castanon & Fedorenko, 2012).

In summary, the comparison of structural processing in language and music in neurological studies provides somewhat of a double view. On the one hand, double dissociations in patient and non-patient studies can be found, suggesting that at least some subcomponents of structural processing are content domain-specific. On the other hand, the overlap found in EEG and neurophysiological measures of structural processing cautiously suggests that domain-specific regions might be linked to more domain-general regions involved in structural processing.

DOMAIN-GENERALITY IN STRUCTURAL PROCESSING

In the previous sections, we have provided a broad introduction to the concept of structural processing and the hypothesis that studying structural processing as completely specific to content domains (music, language, and action) might not be warranted. In favour of this hypothesis, parallels have been discussed in evolutionary, developmental, and neuronal perspectives on structural processing across content domains. In the following section, we will shortly address some theories that have been developed over the past decade which elaborate on the idea of overlap in structural processing across content domains.

Resource Sharing Models.

'Resource sharing' models suggest that the abovementioned combination of double dissociations and neurodevelopmental parallels in structural processing across domains might best be modelled by making a subdivision between structural rule representations on the one hand, and resources supporting structural processing on the other hand. Structural rule representations are said to be domain-specific, and stored in a long-term memory format in distinct associative networks. Hence, these networks, which are susceptible to damage resulting in domain-specific deficits, are often taken to be the cause of dissociations between linguistic and non-linguistic functioning (Tillmann, 2012).

In contrast to the domain-specificity of structural representations however, the cognitive operations of structural processing (which make use of such representations) might be similar across domains. One example, as we have seen in the introduction, is dependency processing. As seen in the DLT (Gibson, 2000) for language and the TPS (Lerdahl, 2001) for music, dependency processing can be resource-intensive, especially in complex materials. Another example is that both linguistic and non-linguistic structure processing is based on expectation generation, where structural complexities are also assumed to be more resource-intensive on the basis of their probability. Hence, the operations (dependency processing, structural prediction) that are conducted on the basis of domain-specific knowledge (linguistic syntax, musical harmony) might in themselves be very similar across content domains and recruit similar resources. On the basis of this, we might be able to account for the similarities that are found in developmental studies and neurophysiological markers for structural processing across domains.

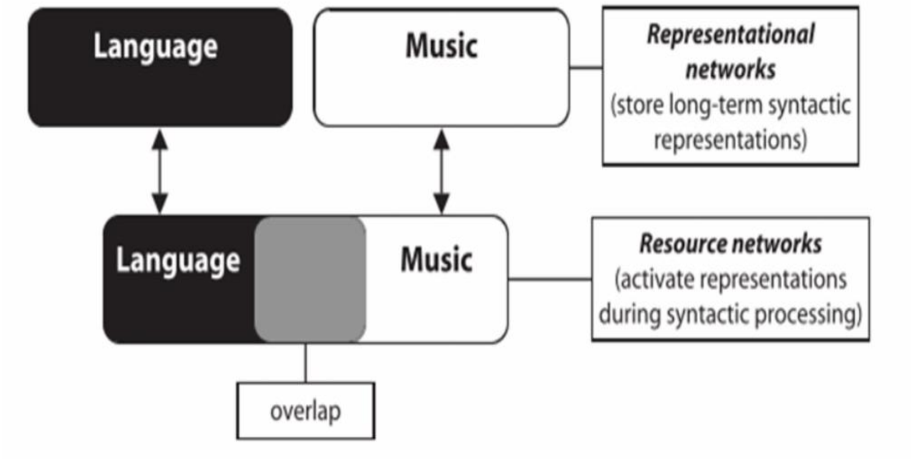

Figure 2: Representation of the SSIRH (Patel, 2008)

Shared Syntactic Integration Resource Hypothesis (Patel, 2003). A first example of a ‘resource sharing’ model can be found in the Shared Syntactic Integration Resource Hypothesis (SSIRH, Patel, 2003), a theory that has gained a lot of attention over the past decade. The SSIRH (see Figure 2) states that overlap in the syntactic processing of language and music can be conceived of as overlap in the neural areas and operations which provide the resources for syntactic integration. Following the abovementioned hypothesis of ‘resource sharing’ frameworks, the SSIRH makes a clear distinction between representational networks on the one hand, and the resources and mechanisms acting on them on the other hand. Patel's hypothesis is extended as the ‘Syntactic Equivalence Hypothesis’ by Koelsch (2012) claiming that music-syntactic processing includes hierarchical processing that is shared with other cognitive systems such as language and action.

Following the abovementioned reasoning, the SSIRH proposes a falsifiable hypothesis; if musical and linguistic syntax processing share neural resources, the simultaneous processing of music-syntactic and linguistic-syntactic difficulties should cause interference, since high demands on joint resources would be made simultaneously across domains. Several studies have provided evidence in favour of this hypothesis (Fedorenko, Patel, Casasanto, Winawer, & Gibson, 2009; Slevc, Rosenberg, & Patel, 2009; Hoch, Poulin-Charronnat, & Tillmann, 2011), by showing interference during the joint structural processing of linguistic and non-linguistic materials, a paradigm which is also used in the first empirical chapter of this dissertation (Chapter 2). To further explain this type of research, three studies will be discussed below.

Behavioural Studies Supporting the SSIRH. Fedorenko et al. (2009) used a listening task to study the interaction of structural processing in the linguistic and non-linguistic domain. They presented participants with sung sentences. These sentences could have a subject-extracted relative clause (e.g., *'the boy that helped the girl got an A on the test'*) or a more complex object-extracted relative clause (e.g., *'the boy that the girl helped got an A on the test'*). Unsurprisingly, lower comprehension accuracies were found for the more complex sentences. Interestingly however, Fedorenko et al. (2009) found that such differences in comprehension accuracy could be amplified when the structurally complex word in the sentences (e.g., 'the boy that the girl *helped*') was sung out-of-key. No such interaction effects were found for amplitude manipulations. The results of this study support the SSIRH, as they suggest an interaction between linguistic and musical processing that seems to be specific to structural manipulations.

In a similar study, Slevc, et al. (2009) provided participants with a self-paced reading task. The experimenters instructed people to read sentences containing syntactic 'garden path' unexpectancies (e.g., 'After the trial the attorney advised the defendant *was* likely to commit more crimes') and semantic unexpectancies (e.g., 'The boss warned the mailman to watch for angry *pigs* when delivering the mail'), which were presented in segments.

With each sentence segment, a chord was provided, resulting in a chord sequence accompanying the self-paced reading of the sentence. Participants showed a longer reading time for sentence segments that contained unexpectancies (both ‘garden path’ and semantic unexpectancies). Providing a harmonically unexpected chord in the melody simultaneously with the unexpected sentence segment increased the time that was needed to process the syntactic, but not the semantic unexpectancies. This evidence again suggests an overlap in resources supporting syntactic integration processes across language and music.

Hoch et al. (2011) also recently investigated the joint structural processing of musical and linguistic materials in a controlled experimental environment. Whereas Fedorenko et al. (2009) and Slevc et al. (2009) focused on behavioural measures of linguistic structure processing, Hoch and colleagues (2011) focused on a structural processing measure for non-linguistic materials. More specifically, they presented participants with a joint processing task in which participants were required to listen to chord sequences when reading sentences. Hoch et al. (2011) investigated tonal facilitation as a measure of music-syntactic processing. Tonal facilitation here refers to the finding that when a melody containing a tonic centre ends on a tonic as compared to a subdominant, the tonic ending will be more structurally congruent and thus facilitate ongoing processing (Escoffier & Tillmann, 2008). Tonic facilitation is hypothesized to be related to the integrational processing of the last tone (tonic or subdominant) into the preceding harmonic structure. Hoch and colleagues (2011) found an interaction between the tonic facilitation effects and simultaneously provided syntactic unexpectancies (but not semantic unexpectancies) in the sentences. In other words, Hoch et al. (2011) showed interactive influences between music-syntactic and linguistic-syntactic processing, but not between music-syntactic and linguistic-semantic processing, which again supports the idea of shared resources for structural processing across domains.

In sum, many studies have found interference during the joint processing of linguistic and musical materials when syntactic difficulties were presented in both domains at once, which seems to confirm the idea of a domain-general pool of structural processing resources as hypothesized by the SSIRH (Patel, 2003).

EEG studies supporting the SSIRH Apart from the behavioural evidence in favour of the SSIRH (Patel, 2003), several EEG studies have also provided evidence suggesting a domain-general pool of structure processing resources. Using joint processing paradigms, the effects of structural processing requirements in one domain have been measured on event-related potentials associated with structural processing requirements in another domain. This kind of research has been further developed in a study reported in Chapter 3 of this dissertation. To provide a perspective of previous EEG research on ‘resource sharing’ models, a few examples are reported below.

Koelsch, Gunter, Wittfoth and Sammler (2005) showed a ‘left anterior negativity' (LAN) when participants read a syntactically incorrect verb in a sentence. In the study, participants were also provided with auditory melodies during the presentation of the sentences, and it was found that when a harmonically unexpected chord occurred simultaneously with the syntactic error, there was a significant decrease in the LAN. Importantly, such a modulation of linguistic processing effects upon hearing an unexpected chord was not found for the N400 related to semantically unexpected words. This specific interference of harmonic violations with neurological measures of syntactic violation processing in language is viewed as evidence for limited and shared resources in the structural integration of both language and music (SSIRH, Patel, 2003).

More recently, a study by Carrus, Koelsch, and Bhattacharya (2011) investigated the patterns of brain oscillations during simultaneous processing of music and language, using visually presented sentences and auditorily presented chord sequences. They showed that both music-syntactically irregular chord functions and syntactically incorrect words elicited a late (350-700 ms) increase in delta and theta-band activity, and furthermore, that this late effect was significantly diminished when the language-syntactic and music-syntactic irregularities occurred at the same time. Therefore, their results suggest that that low frequency oscillatory networks might be shared in the structural processing of language and music.

In another study, Carrus, Pearce, and Bhattacharya (2013) applied a paradigm in which participants read sentences containing a final word that could be unexpected on a syntactic, semantic or combined level. Together with these sentences, melodies were provided with a final tone that would be highly probable or improbable based on the preceding context. In correspondence with linguistic EEG research, LAN and P600 effects were found on the basis of syntactically unexpected words, whereas an N400 was found on the basis of semantically unexpected words (see Koelsch et al., 2005) and both were found in the combined unexpectancies. Interestingly, the LAN effect for syntactically unexpected words was found to be decreased when this word was combined with a low probability tone as compared to a high probability tone. No interactions were found on the N400 effect for semantically unexpected words. This again provides evidence for a sharing of resources supporting structural processing across domains.

Syntactic Working Memory (Kljajevic, 2010). Another example of a 'resource sharing' model can be found in the Syntactic Working Memory account (SWM, Kljajevic, 2010). This account approaches the idea of shared resources from the perspective of working memory. As we have seen, dependency processing models (e.g., DLT, Gibson, 2000), assume a demand on working memory resources to keep current structures in memory and integrate novel elements with these structures. Furthermore, the idea of structural expectancy generation is also related to working memory resources, as it is assumed that more computationally demanding sentential structures make a larger demand on working memory. Hence, it is not surprising that working memory is thought to play a crucial role in structural processing across domains (Stowe, Withaar, Wijers, Broere, & Paans, 2002; Fiebach, Schlesewsky, & Friederici, 2002; Gibson, 1998).

It is important to note the difference between the SSIRH (Patel, 2003) and the SWM (Kljajevic, 2010). One the one hand, the idea of a domain-general pool of resources implied in structural processing is very similar, with structural processing being described as (Patel, 1998, p. 39): *'…the linking of the current input word to past dependents in a string of words, with the assumption that this integration is more costly when dependencies are more distant, when they must reactivate dispreferred structures (as in Gibson, 1998), or when they are simply impossible.')*. Nevertheless, a subtle difference might be found as well. The SSIRH argues for shared 'syntactic integration' resources, which denotes that the resources involved are specified to the processing of syntactic structure (e.g., syntactic 'garden path' unexpectancies like the ones used in Slevc et al., 2009). In contrast, the SWM denotes these resources as working memory resources. Therefore, the resources involved might not be specific to the processing of syntactic structure, but also other forms of structure processing (e.g., semantic structure: 'The old man went to the bank to withdraw his *net* which was empty', where *'net'* can be seen as a semantic 'garden' path word, as it selects an infrequent meaning of *'bank'*, namely a river bank, as presented in Perruchet & Poulin-Charronnat, 2013).

Studies Supporting the SWM. Several studies have supported the Syntactic Working Memory model with similar evidence as has been yielded in favour of the SSIRH (Patel, 2003). For example, the experiment of Fiveash and Pammer (2012) provided participants with the task of listening to melodies while reading and remembering either complex sentences or word lists. The researchers found that presenting harmonic violations in the music (but not instrumental manipulations) interacted with the recognition performance on sentences but not simple words lists, suggesting that such interaction effects are based on the structural nature of the materials that are provided.

In another recent study, Perruchet and Poulin-Charronnat (2013) found that interference during the joint processing of linguistic and non-linguistic materials could be found when using non-syntactic structural difficulties. More specifically, in a paradigm similar to that of Slevc et al. (2009, discussed above), participants performed a self-paced reading task on sentences which could contain structural 'garden path' words, or semantically unexpected words. Together with these sentences, chord sequences were provided. Just like in previous research (Slevc et al. 2009), interactions were observed between the simultaneous presentation of an out-of-key chord and the reading time slowing for a 'garden path' unexpectancy, but not for a semantic unexpectancy. In contrast to Slevc et al. (2009) however, the structural 'garden path' manipulation was not based on the syntactic structure, but on the semantic structure of the sentence (e.g., 'The old man went to the bank to collect his *net* which was empty', as discussed above). The idea that cross-domain interference during joint structural processing can be obtained by both semantic and syntactic 'garden path' manipulations, suggests that it is not the syntactic nature of the unexpectancy but rather the garden path configuration which lies at the basis of the found interference effects. The idea that interactions in the structural processing of linguistic and non-linguistic materials can be found for non-syntactic reintegration, supports 'resource sharing' models focusing on working memory resources (SWM, Kljajevic, 2010) as opposed to syntactic processing resources (SSIRH, Patel, 2003).

Limitations of Previous studies

Whereas the development of 'resource sharing' models has been supported by several behavioural and neurophysiological studies, it should be noted that the previous research on 'resource sharing' accounts has some limitations, which we explain below.

Attention Depletion Accounts. As has been discussed earlier, recent studies (e.g., Perruchet & Poulin-Charronnat, 2013) have found evidence for interference in the structural processing of linguistic and non-linguistic materials, but on the basis of semantic (e.g., 'the man goes the bank to withdraw his *net*') rather than syntactic structure manipulations. One way to interpret this, as mentioned above, is that the resources constituting the previously found interference effects (Slevc et al., 2009; Fedorenko et al., 2009) provide a more general (working memory) support for integrational processing (SWM, Kljajevic, 2010).

However, given that it is not the syntactic nature of the unexpectancy (‘syntax’ versus ‘semantics’, as suggested by the SSIRH, Patel, 2003), but rather the processing incited by the unexpectancy (‘garden path’ unexpectancies versus unresolvable violations) which drives previous findings of cross-domain interactions, explanations other than working memory costs (SWM, Kljajevic, 2010) are difficult to reject. For example, as Perruchet and Poulin-Charronnat (2013) discuss themselves, structural complexities are different from sentential violations not only in their integrational nature, but also in the attentional shifts they incite. One could argue that upon encountering a non-resolvable violation in sentences, participants would shift their attention away from the non-linguistic materials, so that no effects of dual task manipulations can be observed. On the other hand, upon encountering an infrequent interpretation (i.e., a syntactic or semantic ‘garden path’), participants might still jointly process both materials. Interestingly, such alternative accounts for interference in the structural processing of linguistic and non-linguistic materials point out some pain points in previous research, which we will discuss in the following segments.

Performance Measures. One limitation of the previous studies is the type of dependent measures that have been used. For behavioural research, this usually comes down to a measure of general processing performance in linguistic materials, such as comprehension accuracy (Fedorenko et al., 2009) or reading time (Slevc et al., 2009). When a decreased processing of the linguistic material is detected on such measures, it remains very difficult to relate this to a specific component of linguistic processing. These general performance measures are then related to structural processing by contrasting conditions of experimental manipulations (e.g., ‘garden path’ unexpectancy versus semantic unexpectancy) which might allow for alternative interpretations (e.g., the ‘attention depletion’ account mentioned above). The same can be argued for EEG research, in which event-related potentials referring to structural processing are also usually obtained by contrasting different kinds of experimental manipulations. In other words, a main limitation of previous findings is that structural processing is not related to a specific measure, but rather to an experimental contrasting of conditions. As noted in recent papers (e.g., Hoch et al., 2011), the finding of interactions in structural processing across domains is therefore challenged by the difficulty of finding comparable processing difficulties in the experimental manipulations used to isolate structural processing in language.

Ecological Validity. Another remark that can be made on the previous findings, is that (in order to create comparable conditions which can disseminate structural processing effects from general performance measures) highly unnaturalistic materials are used, in highly experimental set-ups. As mentioned earlier, previous research has largely made use of joint processing paradigms, in which materials are provided that contain strong unexpectancies. These unexpectancies are then provided simultaneously to make a domain-general call on structural processing. At this point, it can be questioned how such experimental manipulations relate to our daily processing capacities. After all, most of the language we use does not contain such strong unexpectancies. Furthermore, most music we listen to is pre-recorded and rarely contains harmonic violations. But moreover, the *simultaneous* presentation of such unexpectancies in processing across domains has a very low ecological validity. Therefore, it can be asked to what extent the found interactions between structural processing across content domains are experimentally induced effects, rather than findings that are demonstrative of what is going on in ecologically valid situations.

BI-DIRECTIONALITY AND SEQUENTIAL PROCESSING

The current dissertation is aimed at providing novel perspectives on the study of domain-generality of structural processing, by addressing some of the abovementioned limitations found in research supporting ‘resource sharing’ models.

As we have seen in the previous segment, several studies have provided evidence for ‘resource sharing’ theories through findings of interactions in the structural processing of materials across domains (e.g., Fedorenko et al., 2009; Slevc et al., 2009). However, some debate has risen concerning the limitations of such studies. In these studies, structural processing interactions across domains are approached by contrasting general performance measures between experimentally manipulated conditions which include highly unnaturalistic materials. Such paradigms have given raise to alternative interpretations of the found interaction effects (e.g., 'attentional depletion' account of Perruchet & Poulin-Charronnat, 2013), and hence, the question can be raised what the ecological validity of such interaction effects is. The current dissertation reports research that has attempted to provide a contribution to the research on 'resource sharing' frameworks by addressing two points.

A first is that, whereas many of the previous studies have used measures of linguistic processing to detect interactions in structural processing across domains, we will focus on measures of non-linguistic processing (see Chapter 2). After all, 'resource based' models are bi-directional; resource depletion due to structural processing in language should also influence the ongoing structural processing of non-linguistic materials (see Hoch et al., 2011). This hypothesized bi-directionality of 'resource sharing' accounts might be investigated to a larger extent, as it has been somewhat neglected in previous research. Moreover, whereas the study of structural processing in language is often confounded by referential semantic components, the study of structural processing in non-linguistic materials often entails less complex experimental set-ups (Lerdahl, 2001). Therefore, by studying cross-domain interaction effects on non-linguistic structure processing, it might be possible to find such interactions on more specific measures of structural processing, rather than through an experimental contrasting of conditions.

A second point that will be addressed in the current dissertation is the low ecological validity of the previous joint processing tasks, in which interactions between structural processing of linguistic and non-linguistic materials were yielded by an exact temporal matching of structural difficulties. Though this on-line processing interference is in line with the hypothesis stated by 'resource sharing' models, it must be noted that its ecological validity is certainly questionable. Interestingly however, recent findings in psycholinguistics suggest that sequential influences of structural processing across content domains can also be observed (Scheepers et al., 2011; Scheepers & Sturt, 2014). This idea of sequential influences of structural processing across content domains will be elaborated upon in a following section, as it has been taken as a starting point for the studies reported in Chapters 3, 4 and 5. First, let us take a look at the possibility of measuring structural processing in non-linguistic domains.

Bidirectionality: Investigating Non-Linguistic Structural Integration

As discussed earlier, paradigms focusing on measures of non-linguistic processing might be a valuable tool in investigating structural processing mechanisms across content domains. The study of structural processing in language is often confounded by referential (semantic and thematic) components, whereas the study of structural processing in non-linguistic materials often entails less complex experimental set-ups (Patel, 2008; Winograd, 1968). Hence, whereas it has proven difficult to relate linguistic measures (reading times, comprehension accuracies) directly to the level of structural processing, more transparent measures (see Carrus et al., 2011; Hoch et al., 2011) for structural processing can often be developed on the basis of non-linguistic materials. To provide a perspective on how structural processing in non-linguistic domains can be conceptualized, we will start by discussing harmonic integration as an example of (measurable) structural processing in non-linguistic materials. After all, the non-linguistic materials and measures which have been developed and used throughout the current dissertation, are mainly based on the study of harmonic integration in music.

Harmonic integration as a cognitive function. As has been mentioned in the introduction, harmonic integration (Generative Theory of Tonal Music, GTTM, Lerdahl & Jackendoff, 1983) can be broadly conceptualized as the idea that, with repeated exposure to a culture’s music, listeners implicitly acquire the harmonic regularities on which melodies are based. By (implicitly) applying this knowledge, listeners can then actively process (and predict) the integrational structure of melodies. As we have seen in the previous introduction, this idea of dependency integration and structural expectancy generation is similar to what determines structural processing in language[1]. What makes harmonic integration so interesting as a field of study for structural processing? A few reasons are summed up below.

Harmonic integration without formal knowledge. Since music is often regarded as an acquired skill, focus on musical capacities usually lies with explicitly acquired expertise in instrument playing and music theory. Nevertheless, the structural processing mechanisms which allow us to enjoy music on a daily basis are rather independent from such formal training. Several studies have shown that a wide variety of musical competences (and specifically harmonic integration) are strongly present in adults who have not received an official musical training. For example, the study of Koelsch, Gunter, Friederici, and Schröger (2000) shows that also non-formally trained adults can clearly register violations in harmonic expectancy (e.g., detecting false chords in a melody). This can be seen as evidence that, even without explicit knowledge, the human brain can create a harmonic context and generate expectancies based on auditory input. The ability to acquire (implicit) knowledge of harmonic regularities and to process musical information quickly and automatically on the basis of this knowledge, seems to be a general ability of the human brain (Koelsch & Friederici, 2003). An extensive review concerning the musical abilities of adults with a lack of formal training can be found in the article of Bigand and Poulin-Charronnat (2006).

Harmonic integration in early childhood. It is interesting to note that, sincevharmonic processing in perception is largely dependent on implicit

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[1] Note, however, that in music the word ‘expectation’ might be more suitable than what we would see as a linguistic ‘prediction’, given that musical syntactic relations are expressed in terms of probabilities rather than the obligatory dependencies we find in language. This is also reflected in the idea of a prolongational ‘reduction’ tree structure, as opposed to a sentential hierarchical tree structure (Figure 1).

learning as opposed to formal knowledge, harmonic processing is also a form of structural processing that can be studied across age groups. Though music is something that children are formally taught at a certain age, the basic principles of harmonic processing can be found in very young infants. Several forms of research show strong musical competences in young infants (Trainor & Trehub, 1994). A recent study conducted by Trainor and Corrigal (2010) has for example shown that harmonic sensitivity (i.e., registration of harmonic unexpectancies) can be found as early as around 4 years. Therefore, not only is harmonic processing similar to linguistic structure processing, but furthermore, it can be studied regardless of formal training and across age groups.

Harmonic integration: violations and parsing. How can we measure the extent to which melodies are harmonically integrated? Following the Generative Theory of Tonal Music (GTTM, Lerdahl & Jackendoff, 2009), the harmonic integration of sound sequences entails that participants create expectations concerning upcoming tones on the basis of non-local dependencies (see Koelsch et al., 2013). Such expectations are based on the preceding musical context, in which certain musical tones are more prominent and stable as compared to others. For example, in western tonal music, when creating melodies in a certain scale, the first tone in the scale (‘tonic’) is seen as more of a ‘reference point’ in the harmony (Rosch, 1973; Rosch, 1978), followed by the fifth and third tone (‘dominant’ and ‘mediant’). In any case, the ‘unexpectancy probability’ of incoming tones as previously mentioned is largely dependent on such cognitive reference points.

One effect of expectation-generation in harmonic processing is that sounds which do not conform to the preceding harmonic context (e.g., ‘out-of-key’ chords) will incite strong harmonic violations. This effect is what has mainly been used in previous research on ‘resource sharing’ frameworks (‘out-of-key chords’, Slevc et al., 2009; Neapolitan chords, Steinbeis & Koelsch, 2008). Interestingly however, harmonic integration can also be studied on other levels. For example, when using well-structured melodies, harmonic transitions can take place which are not regarded as harmonic violations, but will lead to a parsing of the melody (e.g., a melody that goes from the C key to the G key). This is similar to the concept of parsing sentences into several phrases (e.g., ‘I see the man | who paints the wall’). The phrase serves as a functional unit, guiding the processing of musical and linguistic materials during perception, and the structuring of such materials in the memory. Parsing is generally regarded as an important way to facilitate the processing of auditory streams (Stoffer, 1985). Studying harmonic parsing effects has the advantage of being directly applicable to well-structured materials. But how can we measure harmonic parsing? One method which is described below, is the use of recognition tasks.

Studying harmonic parsing through recognition tasks. In music cognition, it has been repeatedly shown that the harmonic processing of melodies can influence the recognition performance of those melodies. It has been found that recognition memory for tones is dependent on not only the intervals in the a tonal sequence (Divenyi & Hirsh, 1978), but also on its harmonic context. The importance of musical structure on memory for tones has been demonstrated in a number of studies (Deutsch, 1984). It has for example been shown that tonal melodies are better remembered than random melodies (Cuddy, Cohen, & Miller, 1979; Dewar, Cuddy, & Mewhort, 1977).

Importantly, recognition task differences are not only observed when comparing harmonic melodies to non-harmonic tone sequences, but can also be observed on the basis of harmonic parsing. In early research by Gregory (1978) for example, it was found that when participants were presented with a melody and heard a click within a harmonic segment, they tended to report the time of clicking as occurring between two harmonic segments. In other words, participants erroneously perceived the clicks at times when they detected a harmonic boundary in the melody. Later studies have also consistently found effects of harmonic boundaries on perception and memory (Chiappe & Schmuckler, 1997).

On the basis of the abovementioned research, Tan, Aiello, and Bever (1981) suggested that recognition effects might be used as a measure for harmonic parsing in melodies. In their study, Tan et al. (1981) provided participants with simple tone melodies, after which they were required to judge whether a recognition probe consisting out of two consecutive tones was presented in the previously heard sequence (see Figure 3). The main manipulation of the task was that the experimenters provided harmonic boundaries (instigating a harmonic parsing) at certain moments in the presented tone sequence. Tan et al. (1981) stated that, if the tone sequence would be harmonically integrated, the listener would parse the melody into several harmonic ‘phrases’. This parsing might then hamper the recognition of certain tone sequences as being sequentially provided.

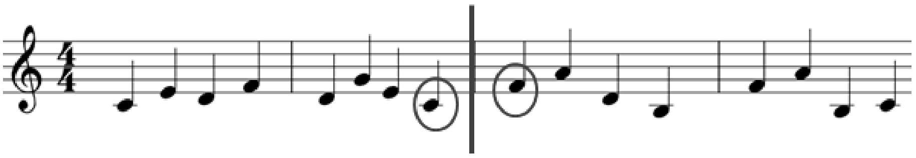

Figure 3: Example of the harmonic integration measure, used by Tan et al. (1981). The line in the melody represents the position of the harmonic boundary. When a harmonic boundary is reached, this leads to a closure of the first musical segment. Therefore, the person will parse the melody on the basis of the harmonic boundary. Because of this harmonic parsing, the two tones tagged in circles (‘between phrase’-probes) will be recognized less well as sequentially occurring as compared to two sequential tones within a harmonic phrase (‘within phrase’-probes).

The dependent variable of the task used by Tan et al. (1981) was relatively simple. When the 'target probes' that needed to be judged were correct, they could either be (a) two consecutive tones that were within the same harmonic 'phrase' after harmonic parsing, or they could be (b) two consecutive tones that were separated by the harmonic boundary, and thus spanned two harmonic ‘phrases’(see Figure 3). The recognition task revealed better recognition performance for ‘within phrase’ probes as compared to ‘between phrase’ probes. This effect was interpreted by Tan et al. (1981) as a harmonic integration effect; the recognition difference is caused by harmonic parsing, following which a 'within phrase'-probe would be perceived more as a consecutive 'chunk' of melody as compared to a 'between phrase'-probe.

In the current dissertation, the recognition advantage for ‘within phrase’ probes over ‘between phrase’ probes has also been taken as a measure of parsing (Chapter 2, 3, 4, and 5). More specifically, we hypothesized that the ‘within probe’ advantage would be larger for structural boundaries which lead to a stronger parsing. This is denoted in the current dissertation as the ‘Boundary Processing Effect’ (BPE); when comparing structural boundaries that have been processed to structural boundaries that have not (or, to a lesser extent) been processed, we would expect a stronger parsing along the well-processed boundaries. This stronger parsing would then lead to a larger ‘within probe’ advantage, since the ‘within probe’ performance would be contrasted to performance on a more strongly segmented ‘between probe’.

Recognition tasks and formal training. When studying harmonic parsing, it remains hard to determine to what extent harmonic processing effects (like the recognition effects mentioned earlier) are caused by implicit or explicit parsing of the melody. It is generally agreed upon that, whereas the structural processing of language happens rather implicitly, harmonic processing is strongly influenced by whether or not the participant can rely on explicit knowledge of music theory (Koelsch, Schmidt & Kansok, 2002). Thereby, the study of harmonic as compared to linguistic processing might be different in the extent to which formal knowledge of structural rules is applied.

When relating this remark to the recognition measure of harmonic integration that has been previously mentioned, it is important to acknowledge that recognition effects for harmonic melodies might be related to participants’ knowledge of music theory. In fact, the original study by Tan et al.(1981) did find that the ‘within probe’ advantage effect was stronger for more experienced musicians, suggesting at least some additional effects of formal knowledge. To account for this, the current dissertation reports studies which test the structural processing of experimentally created pitch sequences which are not composed following tonal harmony.

Development of Structural Pitch Sequences. For the current dissertation, pitch sequences were developed containing an experimentally manipulated integrational structure. Importantly, though this structure was loosely based on typical pitch congruency in Western Tonal Harmony, the pitch sequences did not follow a harmonic composition, so that participants would need to implicitly acquire the structural rules regardless of their musical training.

To create the structured pitch sequences, we differentiated three clusters of harmonically congruent tones (all in the key of C). There was an 'A E B' cluster, a 'F C G' cluster and an 'Eb Ab Db' cluster, as is represented in Figure 4. The clusters consist out 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 neighbouring on average as compared to pitch transitions between clusters. This might aid participants in their acquisition of the pitch clusters. Importantly however, the pitch clusters themselves would have to be implicitly acquired in the experiment, as the pitch sequences do not correspond to a harmonic composition on the basis of formal music theory.

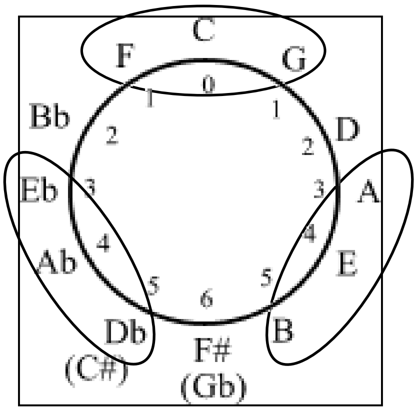

Figure 4: Overview of the pitch clusters

Recognition Task on Structured Pitch Sequences. To investigate to what extent participants accurately process the experimentally induced structure of the pitch sequences, the recognition task as reported by Tan et al. (1981) can be applied. Though the pitch sequences are not 'musical', or created based on tonal harmony (a requirement to ensure that the structuring effort was not dependent on musical knowledge), they contain structural boundaries which are based on easily acquired grouping rules (i.e., the abovementioned pitch clusters). Therefore, we still expect a Boundary Processing Effect when comparing pitch sequences with a processed pitch cluster boundary to pitch sequences where this pitch cluster boundary was not processed.

Sequential Influences of Structural Processing: Structural Priming

As mentioned earlier, a second point that we attempted to address in the current dissertation, is the low ecological validity of the materials and paradigms used thus far in studies supporting a domain-general pool of structural processing resources (e.g., Slevc et al., 2009; Hoch et al., 2011). For this, we investigated to what extent interactions in structural processing across domains could be observed when studying the sequential processing of well-structured materials (see Chapters 3, 4 and 5). To study sequential influences in structural priming across domains, we mainly directed ourselves to the literature on structural priming.

Structural Priming in Language. Structural priming is a commonly used paradigm in psycholinguistic research. Structural priming paradigms are based on the finding (e.g., Bock, 1986) that after processing a sentence which contains a certain syntactic structure (e.g., *'the clown is tickled by the swimmer'*) people show a higher preference for using a similar structure in consecutive production (e.g., describing a picture with another passive, *'the waiter is kissed by the prisoner'*, as opposed to using the active description *'the prisoner kisses the waiter'*). Interestingly, previous research has found that such priming of sentential preferences is not related to prosody (Bock & Loebell, 1990), and that it does not require any lexical items or thematic roles to be overlapping between the priming description and the subsequent description (Ferreira & Bock, 2006). These structural priming effects are reviewed in a comprehensive paper by Pickering and Ferreira (2008).

Most accounts for structural priming assume that this phenomenon is caused through an activation of syntactic representations. A well-known model on such 'syntactic representation priming' is the model of Pickering and Branigan (1998). In this model, verbs are related to local syntactic representations (e.g., the verb *'to send'* would be linked to a node representing a double-object dative like *'send the boy the present'*, and also to a node representing a prepositional object dative like *'send the present to the boy'*). An activation of these syntactic representations during the processing of a sentence would then make the selection of that same syntactic representation in a following sentence production more likely (for a more extensive discussion, see Pickering & Branigan, 1998).

There are several models on how exactly syntactic representations guide structural priming. An influential account is that of Chang, Dell and Bock (2006), who propose that structural priming is the result of an error-based, implicit learning of syntactic rules. This is to say, when participants are incrementally processing sentences which are infrequent (e.g., in Dutch, a double object dative like *'the girl gives the baby the present'* occurs less as compared to a propositional object dative like *'the girl gives the present to the baby'*), then they would encounter a structural unexpectancy at some point (e.g., when reading 'the girl gives the baby *the present*', this last sentence segment indicates a double object dative structure, where on the basis of probability, a prepositional object structure like 'the girl gives the baby *to the mother*' might be expected). This unexpectancy would then serve as an 'error signal' which incites an updating of the connectionist network of syntactic representations, so that this structure would be selected with a higher probability in the processing of upcoming materials.

In any case, several models suggest that structural priming is based on structural integration representations, which are governed by language-specific rules (Pickering & Ferreira, 2008). In what way could structural priming then be used to study structural processing across domains? An answer might be found in the recent study of structural attachment priming (Scheepers, 2003).

Structural attachment priming. Over the past decade, structural priming findings have emerged which do not seem to rely on the activation of (language-specific) syntactic rule representations. Scheepers (2003) reported structural priming on the basis of sentences that were developed under the same syntactic rules. More specifically, he found structural priming effects based on the attachment site of relative clauses. For example, consider the difference in interpretation of the sentence *'I see the tables of the room that are wide'* as compared to the sentence *'I see the tables of the room that is wide'*. Both sentences contain the same structure on a lexical level, as well as the same order of syntactic rules (see Figure 5). However, there is a difference in their global structure. In the sentence *'I see the tables of the room that is wide'*, the relative clause (*'that is wide'*) refers to the second noun phrase (*'the room'*), which is called a low attachment structure (LA) given that the relative clause directly attaches to the preceding prenominal clause (*'of the room'*). On the other hand, in the sentence *'I see the tables of the room that are wide'*, the relative clause (*'that are wide'*) refers to the first noun phrase in the sentence (*'the tables'*), which is called a high attachment structure (HA), given that the relative clause surpasses the pronominal clause and attaches directly to the NP in the main clause ('*the tables*').

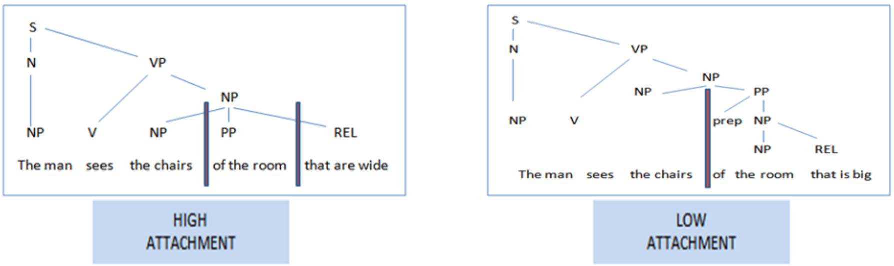

Figure 5: Example of a high attachment and low attachment relative clause sentence

Scheepers (2003) found that the preferred attachment in relative clause completion (e.g., asking participants to complete the sentence *'the boy sees the kittens of the cat that….'*) could be primed by a previous processing of HA versus LA relative clause sentences. Such relative clause attachment priming has been shown to occur across languages (e.g., Dutch and English; Desmet & Declercq, 2006), and sentence structures (e.g., between the attachment of prepositional phrases and relative clauses; Loncke, Van Laere, & Desmet, 2011).

What is interesting about this form of structural priming in relationship to the study of domain-generality of structural processing, is that the relevant structural contrast in relative clause priming concerns the hierarchical configuration of the sentence, rather than the phrase structure by which such a configuration is constructed. In other words, one might state that the priming of structural attachments relies on structural integration mechanisms, rather than the (language-specific) syntactic rule representation on the basis of which these mechanisms operate. Following the previously discussed ‘resource sharing’ accounts, it might thus be possible that attachment priming operates across content domains.

Cross-domain attachment priming. In recent studies, priming evidence has indeed been found in support of a domain-general nature of structural attachment priming. In a study by Scheepers et al. (2011), structural attachment priming was found from simple arithmetic equations to the completion of relative clause sentences. The mathematical equations contained a certain bracket structure governing their solution, which corresponded to a HA or LA structure. For example, *’80 – 9 + 1 x 5’* corresponds to a LA structure, whereas *’80 – (9 + 1) x 5’* corresponds to a HA structure. The idea that such HA versus LA constructions, created in a non-linguistic domain, can structurally prime subsequent relative clause sentence completions, argues strongly in favor of attachment priming being based on domain-general features of structure processing. Furthermore, it is noteworthy that the structural priming effect was modulated by the arithmetic performance of the participants. Participants with a low grasp of the arithmetic rules of operator precedence did not show structural priming.

More recently, a study by Scheepers and Sturt (2014) demonstrated structural priming from language to arithmetic equations and vice versa. The mathematical equations were right-branched (e.g., *'3+5*2'*) or left-branched (e.g., *'3*5+2'*), and participants were asked to complete these. The linguistic materials were right- or left-branching adjective-noun-noun compounds (e.g., *'alien monster movie'* or *'lengthy monster movie'*), on which participants gave plausibility judgements. Scheepers and Sturt (2014) found that participants provided more correct solutions to the mathematical equations when their branching was congruent with the preceding linguistic prime, and that participants also provided higher plausibility ratings for linguistic materials which were congruent with the structure of preceding mathematical equations. In other words, a bidirectional structural priming could be observed across linguistic and non-linguistic materials.

Such cross-domain priming results are very interesting in the light of the current research topic, as they provide evidence for interactions in the structural processing of materials across domains, but through the use of ecologically valid materials, in a more naturalistic set-up as compared to joint processing tasks.

CURRENT RESEARCH

From the presented introduction, we can retain the following elements. Structural processing, as a cognitive function, has largely been modelled as specific to content domains (e.g., linguistic syntax versus tonal harmony). Nevertheless, strong parallels in structural processing can be found across content domains. Over the past decade, several studies have therefore attempted to directly address the hypothesis (postulated by 'resource sharing' models like the SSIRH, Patel, 2003, or the SWM, Kljajevic, 2010) that whereas structural rules are acquired and represented in domain-specific networks, the resources supporting the processing of incoming information along these rules might be domain-general. Through the use of joint processing paradigms (e.g., Slevc et al., 2009), interference has been found when simultaneously presenting structural difficulties in linguistic and non-linguistic materials. This does indeed suggest that structural processing across domains is based on a shared pool of resources. However, there are some limitations to this form of evidence. One is that, since previous studies have focused on structural processing in language, interference has mainly been interpreted from quite general measures (e.g., reading times) through the contrasting of conditions, leaving open other alternative explanations for the found interference (Perruchet & Poulin-Charronnat, 2013). Furthermore, the use of a simultaneous presentation of structural unexpectancies has a low ecological validity. Therefore, it can be questioned how the obtained interference findings relate to our everyday functioning.

Following this discussion of the research field, we have proposed two novel perspectives on the study of domain-generality in structural processing. A first perspective is the development of a measure for non-linguistic structure processing, on the basis of which joint processing studies can more specifically address structural processing effects without contrasting conditions. A second perspective is the use of structural priming paradigms, more specifically attachment priming (Scheepers et al., 2011) to address interactions between the structural processing of linguistic and non-linguistic materials through the use of more naturalistic paradigms and materials.

In the next chapters, we will report the research that has been conducted for the current dissertation. In Chapter 2, we have applied the recognition task measure to study the influence of structural processing difficulties in language upon the structural integration of our experimentally manipulated pitch sequences. This way, we address the concerns about alternative theories on previously found interference effects during joint structural processing (Perruchet & Poulin-Charronnat, 2013). In Chapter 3, we provide an EEG study in which we investigate whether interactions in structural processing across domains are limited to on-line resource interference. Subsequently, in Chapters 4 and 5, we address the recent cross-domain structural priming findings of Scheepers et al. (2011, 2014), and their relationship to 'resource sharing' models for structural processing across domains.

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CHAPTER 2

SHARED STRUCTURING RESOURCES ACROSS DOMAINS: DOUBLE TASK EFFECTS FROM LINGUISTIC PROCESSING ON THE STRUCTURAL INTEGRATION OF PITCH SEQUENCES[1]

Many studies have reported evidence suggesting that resources involved in linguistic structural processing might be domain-general, by demonstrating interference from simultaneously presented non-linguistic stimuli on the processing of sentences (Slevc, Rosenberg, & Patel, 2009). However, the complexity of the analysed linguistic processes often precludes the interpretation of such interference as being based on structural - rather than more general - processing resources (Perruchet & Poulin-Charronnat, 2013). We therefore used linguistic structure as a source of interference for the structural processing of non-linguistic materials, by asking participants to read sentences while processing experimentally manipulated pitch sequences. Half of the sentences contained a segment with either an 'out-of-context' sentential violation or a 'garden path' unexpectancy. Furthermore, the pitch sequences contained a cluster shift, inducing a structural boundary which did or did not align with the sentential unexpectancies. A two-tone recognition task followed each pitch sequence, providing an index of the strength with which this structural boundary was processed. When a 'garden path' unexpectancy (requiring structural reintegration) accompanied the cluster shift, the structural boundary induced by this shift was processed more shallowly. No such effect occurred with non-reintegratable 'out-of-context' sentential violations. Furthermore, the discussed interference effect can be isolated from general pitch recognition performance, supporting the interpretation of such interference as being based on overlapping structural processing resources (Kljajevic, 2010; Patel, 2003).

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[1] Van de Cavey, J., Severens, E., & Hartsuiker, R. J. (2016). Shared Structuring Resources across Domains: Double task effects from linguistic processing on the structural integration of pitch sequences. *Quarterly Journal of Experimental Psychology*, In Press

INTRODUCTION

The organisation of discrete elements into a hierarchical structure is a necessary component in language comprehension. The syntactic rules of a language, governing the relation between words, allow for complex structures to be produced and interpreted. It is important to note that this function, though studied extensively in the domain of language, pertains to other domains as well. Music for example also involves a specific set of rules that govern the structuring of sequences and combinations of musical notes (Patel, 2003, 2008). Similarly to our capacity for language processing, our ability to process musical structure seems to be based on mere exposure to the rule set, rather than formal training (Koelsch, 2005; Koelsch, Gunter, Friederici, & Schröger, 2000). The structural processing of sequences thus seems to have analogies between language and music.

In recent years, there has been an increase of interest in such findings of similarity across the structural processing of linguistic and non-linguistic materials. Several neurophysiological studies have shown large overlap in the brain areas and ERP components underlying linguistic and musical processing (Maess, Koelsch, Gunter, & Friederici, 2001; Patel, Gibson, Ratner, Besson, & Holcomb, 1998), suggesting that strongly aligned, if not overlapping, processes might be at work. This suggestion of overlap in structure processing across domains has been further developed by Patel (2003), who proposed the Shared Syntactic Integration Resource Hypothesis (SSIRH). Specifically, this model distinguishes between (a) the representational networks, which store long-term knowledge that guides structural integration, and (b) the limited (neural) resources which are dedicated to structural integration. The SSIRH claims that, whereas the representational networks are domain-specific, the resources that are needed for structural processing on the basis of these representations may strongly overlap between domains (as presented in Figure 1).

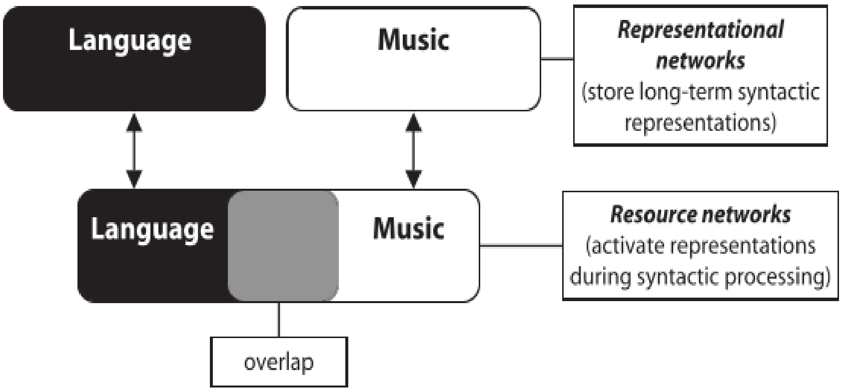

Figure 1: Overview of the SSIRH as adapted from Fedorenko, Patel, Winawer & Gibson (2009)

The SSIRH model makes predictions about situations where music (as a specific non-linguistic domain) and language are processed simultaneously. During such joint processing, structural integration processes in both domains would make a demand on a single, shared resource pool. Therefore, providing a structural integration difficulty simultaneously in both domains should lead to a depletion of resources, so that the structural processing in one domain would interfere with the structural processing in the other domain. This claim was tested by Slevc, Rosenberg, and Patel (2009) in a self-paced reading task. They found that during the simultaneous processing of chord sequences and sentences, the presentation of harmonic unexpectancies increased the slowdown found during the reading of syntactic ‘garden path’ unexpectancies. In contrast, harmonic unexpectancies did not modulate the effects of semantic unexpectancies in sentences. Slevc et al. interpreted these findings as direct evidence for the SSIRH’s claim for shared structural integration resources. Furthermore, similar linguistic influences on music-related ERP measures have been found. For example, Steinbeis and Koelsch (2008) found a reduced early Right Anterior Negativity (eRAN, associated with processing structural difficulties in music) when a syntactic (but not a semantic) unexpectancy was presented in a sentence simultaneously with a harmonic unexpectancy.

Although these previous studies support the claims of the SSIRH (Patel, 2003), several questions remain to be further addressed. For example, neurophysiological studies (e.g., Steinbeis & Koelsch, 2008) find influences from linguistic processing on musical processing, suggesting that the behavioural effects found by Slevc et al. (2009) might only reveal one side of a bidirectional influence. Such a claim follows the SSIRH, which predicts that the sharing of syntactic integration resources will lead to interference during simultaneous processing of music and language, both when participants are asked to respond to linguistic as well as to non-linguistic materials. However, research still needs to further address the possibility of interference effects on direct measures of structural integration in non-linguistic stimuli.

Also, previous research has, either neurophysiologically (Steinbeis & Koelsch, 2008) or behaviourally (Slevc et al., 2009), measured structural processing by investigating the additional effect of processing difficulties in one domain on unexpectancy resolution in the other domain. It might be worthwhile to investigate whether such interference can also be found when the processed materials contain no such unexpectancies. Do we find interference only when measuring reintegration processes or also when measuring the processing of structurally sound materials? In our study, we investigated the processing of structural unexpectancies in the linguistic domain upon the integrational processing of structurally robust pitch sequences.

Furthermore, Perruchet and Poulin-Charronnat (2013) showed that previous findings of interference between the processing of harmonically unexpected chords and simultaneously presented syntactic ‘garden path’ disambiguation (e.g., *‘After the trial the attorney advised (that) the defendant was likely to commit more crimes’*, Slevc et al., 2009), could be replicated using a semantic ‘garden path’ unexpectancy (e.g., *‘The old man went to the (river) bank to withdraw his net which was empty’*).

This finding has two implications. First, the finding of such an interaction between music and semantic reintegration suggests that the reintegration process, more so than the syntactic rules on which it is based, drives the previously found interference effects. This suggests a more broad interpretation of ‘structural integration mechanisms’ as described by Patel (1998, p. 39: *‘For language, I mean the linking of the current input word to past dependents in a string of words, with the assumption that this integration is more costly when dependencies are more distant, when they must reactivate dispreferred structures…, or when they are simply impossible.’*). The recent topic of debate (e.g., Perruchet & Poulin-Charronnat, 2013) thus suggests that further research might benefit from using ‘dependency processing’ as a central concept across syntax and semantics (in contrast to the narrow definition of ‘syntactic’ processing resources by the SSIRH, Patel, 2003). Indeed, several recent theories investigating structural processing across domains (such as the Syntactic Working Memory account, Kljajevic, 2010) proposed an overlap in resources, required for processing (syntactic or thematic) dependencies between elements. Importantly, also in the current study, we interpret both the SSIRH (Patel, 2003) and the SWM (Kljajevic, 2010) as models suggesting an overlap in resources involved in processing the dependencies of integrational structures.

Second, the finding of interference between harmonic incongruency processing and semantic garden path disambiguation also raises some concerns about the theoretical interpretation of previous studies (e.g., Slevc et al., 2009). Given Perruchet and Poulin-Charronnat’s (2013) findings, it seems that cross-domain interference during unexpectancy processing can be found for both semantic and syntactic garden paths, but not for semantic violations. Therefore, it seems that such interference depends on the processes involved in dealing with the unexpectancy (i.e., garden path unexpectancy versus simple violations), and not the unexpectancy being semantic or syntactic in nature. This shift in interpretation has led to the suggestion of a possible confound with attention (Perruchet & Poulin-Charronnat); if it is the complexity nature of the unexpectancy that distinguishes whether interference is found, then other aspects of the contrasting conditions (like attention allocation) could play a large role. Such accounts need further investigation.

To address the abovementioned research questions, we have elaborated upon the paradigm of Slevc et al. (2009), contrasting the effect of ‘garden path’ sentence unexpectancies that instigate a reconstruction of the abstract hierarchical representation, as contrasted to a highly frequent baseline structure involving the second noun phrase as a patient, with the effects of sentence unexpectancies in which the critical word is ‘out-of-context’ and thus does not involve a manipulation on the level of dependency relationships within the sentence.

Similar to Slevc et al. (2009), these sentences will be provided simultaneously with rule-governed auditory sequences. In contrast to earlier studies however, we will use the structural processing of these auditory sequences as a dependent measure, allowing us to investigate possible interference effects on basic non-linguistic integrational processing. Importantly, these auditory sequences themselves contained no unexpectancies, allowing us to measure the integrational processing of structurally robust materials. Also, we should note that we have used tone progressions in the present study, as opposed to the chord sequences used in previous studies (Slevc et al., 2009). This change was made to simplify the non-linguistic structure to a simple pitch sequence structure, which allowed for the integrational processing measure we explain below.

Measuring structural integration through recognition

To create a measure of structural integration processing in a non-linguistic domain, we have adapted the probe recognition task used by Tan, Aiello, and Bever (1981). Tan et al. provided participants with a melody which they were required to listen to attentively. During a subsequent two-tone probe recognition task, participants judged whether the two probe tones were present in the preceding melody (in the same order). Importantly, Tan et al. included a harmonic boundary in the melody, so that upon processing its harmonic structure, the melody would be perceived as two-phrased (see Figure 2).

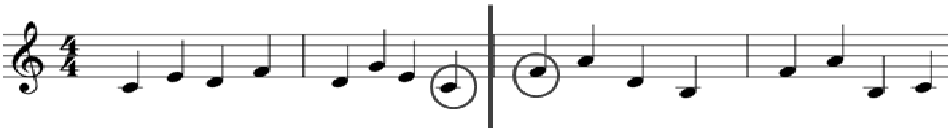

Figure 2: Illustration of the harmonic integration effect found by Tan et al. (1981). The line in the melody represents the position of the harmonic boundary. Following the tone in the left circle (just like any other tone), participants form harmonic expectations concerning the pitches that might follow. On the basis of such expectations, a harmonic boundary is detected. This leads to a closure of the first musical segment, and a harmonic parsing of the melody into two phrases. As a result, the sequence of the two tones tagged in circles ('between phrase'-probes) will be recognized less well as compared to any other two sequential tones ('within phrase'-probes).

Tan et al. (1981) observed that participants found it significantly harder to accurately recognize the probe tone pair if these tones were separated by such a harmonic boundary. Moreover, this recognition effect was stronger with participants who had more musical experience aiding them in detecting this harmonic shift (around 7.5 % for non-musicians, versus around 28 % for musicians). Tan et al. argued that the difference in performance on the 'between probes' (i.e., recognition probes consisting of the tones spanning the harmonic boundary) versus the 'within probes' (i.e., recognition probes consisting of tones within a harmonic phrase), was due to the participants having a parsed representation of the melody. This 'within probe' advantage on the recognition task would occur since, upon processing the harmonic boundary in the melody, the representation of the melody would have an increased sequentiality of tones within a same harmonic phrase (sampled in 'within probes'), and it would have a decreased sequentiality of the tones spanning a harmonic boundary (sampled in 'between probes').

In other words, the authors argued that the 'within probe' advantage on the recognition task is a result of structural integration of the melody, leading to a parsed representation of the melody. We denote this effect as the boundary processing effect (BPE); when comparing pitch sequences that are structurally processed to pitch sequences that are not structurally processed, the recognition of 'between probes' (spanning pitch boundaries) will be decreased and the recognition of ‘within probes’ (within pitch boundaries) will be increased, leading to a ‘within probe’ advantage.

In this study, we used non-linguistic pitch sequences, which also included structural boundaries. Though these pitch sequences are not ‘musical’, or created based on tonal harmony (a requirement to ensure that the structuring effort was not dependent on musical knowledge), they contained boundaries based on easily acquired grouping rules. The reason for this choice is that we wanted to avoid any influence of explicitly acquired knowledge (e.g., music theory) during the processing of the pitch sequences. Regardless of these differences, we still expect a BPE when comparing pitch sequences with a processed boundary to pitch sequences where this boundary was not processed. To be able to replicate the BPE in our task, we needed to allow for good recognition performance. This is why, instead of the chord sequences provided in earlier experiments (e.g., Slevc et al., 2009; Perruchet & Poulin-Charronnat, 2013), we opted for simple tone sequences.

Current study

In this study, we addressed the claim that structural processing of both linguistic and non-linguistic materials might draw on the same pool of resources (SSIRH, Patel, 2003). In contrast to previous research (Slevc et al., 2009), which has focused on a linguistic measure of interference, we aimed to test whether there is interference from linguistic upon non-linguistic processing. Based on the SSIRH (Patel, 2003), we predicted that providing structural integration difficulties in language and structural boundaries in non-linguistic pitch sequences simultaneously should lead to interference. Such interference should occur only when a linguistic unexpectancy is provided simultaneously with the structural shift in the pitch sequence, and when this linguistic unexpectancy triggers a reintegration of the sentential structure (garden path unexpectancies, but not unexpectancies that are ‘out-of-context’ to the sequence and thus do not trigger dependency processing; Perruchet & Poulin-Charronnat, 2013; Slevc et al., 2009).

We predicted a BPE (i.e., better performance on ‘within probe’ recognition and worse performance on ‘between probe’ recognition) in the conditions where we expect intact processing of the boundary (all no overlap conditions, and the overlap conditions using sentences containing an ‘out-of-context’ violation), compared to the condition where we expect poor boundary processing (the overlap condition where the sentence contained a ‘garden path’ unexpectancy which overlapped with the presentation of the pitch structure boundary). Thus, we expect a three-way interaction between probe type (within vs. between), overlap (overlap vs. no overlap), and sentence type (‘out-of-context’ vs. ‘garden path’ unexpectancies), reflecting a decreased ‘within probe’ advantage when there is an overlap between the sentence manipulation and the structural boundary in the pitch sequences, but only when the sentence manipulation is a garden path unexpectancy.

METHOD

Participants

We recruited 40 participants from the student pool of Ghent University (average age = 18, age range 17-21, 4 men, 36 women), who participated for course credits. We ran participants until the predetermined sample size of 40 was reached. Because of the limited availability of participants during certain periods of the year, there was a time gap between testing the first and the second group of 20 people. Grouping based on testing moment was included as a control variable in our design, but yielded no statistical differences. No participants were removed. Participants were not selected on the basis of their musical abilities, given that the pitch sequences did not consist of tonal compositions based on Western Tonal Harmony.

However, after obtaining informed consent for the experiment, we measured the number of years spent on formal musical training (which ranged from 0 to 11 years, mean of 2.65 years), and included that variable in our analyses, as to control for possible explicit tracking of pitch clusters (which might be possible for people with high musical training).

Materials

Sentences. We presented three sentence types in Dutch, namely control sentences, sentences containing a garden path unexpectancy, and sentences containing an ‘out-of-context’ unexpectancy (i.e., a word category violation, where a noun replaces a verb). The stimulus list consisted of 96 sentences, preceded by 4 practice sentences. Each sentence contained eight segments. 50% of the sentences were control sentences (48), which always had the following surface structure: ‘Imperative verb | noun phrase | complementizer | noun phrase | passive participle | auxiliary | preposition | noun phrase’. An example sentence is *‘Zeg | de arts | dat | zijn zoon | ontvangen | wordt | in | de hal’* (meaning ‘tell | the doctor | that | his son | received |is | in | the hallway’, word-by-word translation, or ‘tell the doctor that his son is received in the hallway’). We used a fixed sentence structure for all control sentences in order to create a strong expectation for the passive voice in the complement clause of garden path sentences as well.

The other 50% of the sentences consisted of experimental sentences (48), which contained linguistic unexpectancies. Of these experimental sentences, half contained an ‘out-of-context’ violation, which took place either at the third or sixth sentence segment and which did not allow for any possible revision. For example, a sentence with a violation at the sixth segment would be ‘*Vraag | de directeur | of | de dossiers | opgehaald | plek | door | de secretaris’* (meaning ‘ask | the director | if | the files | fetched | PLACE |by |the secretary’, word-by-word translation). The other half of the experimental sentences contained a ‘garden path’ ambiguity, with the disambiguating word either at the third or the sixth sentence segment. An example of disambiguation at the sixth segment would be *'Vraag |de agent| of | de inbreker |onderschept |welke | berichten |er zijn'* (meaning 'Ask |the policeman | whether |the burglar | caught |WHICH |messages |there were', word-by-word translation).The correct reading of the 'garden path' sentence has a different structure from the control sentences, hence we assumed that the participants would often initially adopt the garden-path reading of a passive voice in the complement clause (i.e. *' the burglar caught'* would be expected to be followed by *'was'*, making *'the burglar'* the patient of the verb) , both because of the verb's semantics (i.e., a burglar is likely to get caught) and in light of the high frequency of a passive voice in the complement clause in the experiment overall. Importantly, once the infelicity of the initial reading is detected, a reconstruction of the sentential structure is possible, which leads to a comprehensible sentence. For an overview, see Appendix 2 at the end of this dissertation.

Pitch sequences. The pitch sequences consisted of 8 pitches, which were created out of sine waves and had a fixed duration of 230 ms, separated by 70 ms silences. Their frequencies ranged from 196.00 to 698.46 Hz and corresponded to 18 pitches: G3, Ab3, A3, B3, C4, Db4, Eb4, E4, F4, and the same set repeated one octave higher. To create experimentally manipulated structural boundaries, we applied a novel grouping rule on pitch sequences, thus being able to create and break a simple expectancy pattern that could be easily acquired. We subdivided the pitches that could be presented into three clusters: notes A-B-E, notes Ab-Eb-Db, and notes C-F-G (See Figure 3).[2]

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[2] Please note the clustering presented in Figure 3. We grouped tones into pitch clusters on The Circle of Fifths, separating each cluster by maximally one tone. When regarding the Circle of Fifths as an overview of harmonic closeness, we can thus see that within-cluster transitions (e.g., G to F) can be similar in harmonic closeness as compared to between-cluster transitions (e.g., F to Eb). The clustering further did not follow harmonic composition.

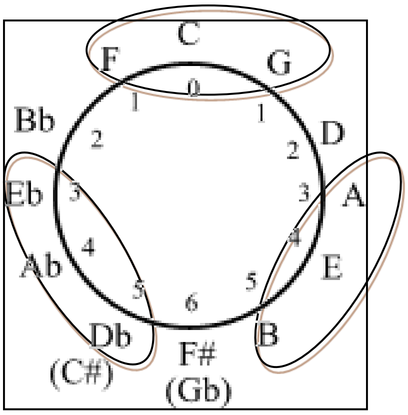

Figure 3: Overview of the pitch clusters

Whereas the first tone was randomly selected out of all 18 possibilities, the following tones were randomly chosen to be one of the two closest neighbours (in frequency) above or below the preceding tone, selected within the same cluster. Importantly, there was no other structure in the sequences, except for this cluster grouping. Therefore, it was expected that their underlying structure would be easily acquired regardless of formal music knowledge. An illustration can be found in Figure 4. For every trial, a pitch sequence was randomly created with the abovementioned characteristics.

Importantly, a cluster shift was included in all pitch sequences. This cluster shift encompassed that a pitch was taken randomly from all pitch possibilities outside the pitch cluster of the preceding pitch. For example 'A B A | G C F G C' includes a cluster shift from the third to the fourth pitch, where there is a shift from the 'ABE' to the 'CFG' cluster. The position of this cluster shift occurred either on the 3rd-4th pitch (50%) or the 6th-7th pitch (50%), and was manipulated to investigate the effects of overlap with the sentence irregularities presented at the 3rd or 6th sentence segment. We chose to align the linguistic unexpectancy with the pitch preceding the cluster shift, given the fast presentation time of each segment (370 ms), so that the cluster shift would be detectable within 400 ms after the linguistic unexpectancy presentation, which should create overlap (see procedure).

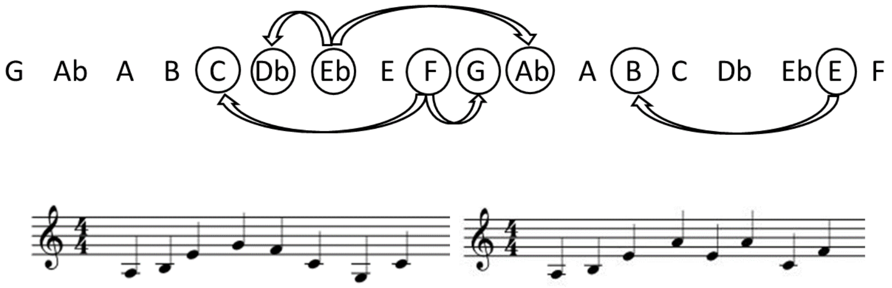

Figure 4: Overview of the pitch sequence construction. On top of the figure, an overview of the pitch sequence creation is being presented. Tones were selected so that each following tone was either the closest neighbour above or below the preceding tone. For example, F4 could be either followed by C4 or G5, whereas for example E5 could only be followed by B5.

For the recognition probes, the ‘between probes’ (1/3 of trials) were selected to be the two tones spanning the shift in the preceding pitch sequences. The ‘within probes’ (1/3 of trials) were selected randomly from all possible segments of 2 sequentially presented pitches in the preceding pitch sequence that did not span the cluster shift. The ‘foil probes’ (1/3 of trials) were incorrect recognition probes, and consisted of a random combination of two pitches that were presented in the preceding sequence, but not in that sequential order.

Procedure

Participants received task instructions and then performed four practice trials to familiarize themselves with the experiment. After practice, participants performed 96 trials, with each trial consisting out of a simultaneous presentation of pitch sequences and sentence segments, followed by a pitch recognition task (Figure 5). The presentation of the trials was randomized. To indicate the start of a trial, a fixation cross was presented for 500ms. After this, the eight sentence segments were presented in Arial 12 font against a black background, for 370 ms, separated by 200 ms breaks. The onset of pitches was aligned with the onset of the sentence segments. After presentation of the complete sentence and pitch sequence, the participants heard a two pitch fragment. They judged whether this two-pitch fragment had occurred in the previously heard pitch sequence by clicking left or right for ‘correct’ or ‘incorrect’, respectively. After this judgment, a fixation cross appeared and the next trial started. However, to ensure attentive reading, a button appeared instead of the fixation cross on eight random trials. Participants were instructed to then write down the previously read sentence on the back of their music questionnaire, before clicking the button to continue; they performed this reproduction task accurately in 79% of the cases. Furthermore, participants received 20 easy comprehension prompts randomly dispersed across trials, as to heighten the attention towards sentence processing. No trials were removed.

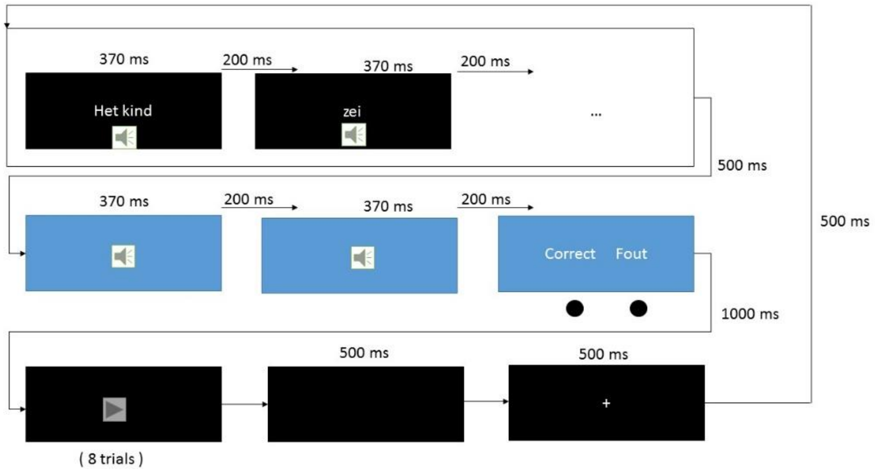

Figure 5: Overview of the experimental procedure. The screen with the blue button was only provided on 8 random trials, indicating that participants were to write down the sentence before continuing.

Design and Analyses

The experiment had a 2 (‘overlap’ / ‘no overlap’ between unexpectancy and pitch cluster boundary) X 3 (‘control’ / ‘garden path’ unexpectancy / ‘out-of-context’ violation) X 3 (recognition of ‘between probe’/ ‘within probe’/ ‘foil probe’) design. All variables were manipulated within-participants. We ran lmer analyses, treating years of formal training, sentence condition, critical overlap (between linguistic unexpectancy and pitch boundary), and probe condition as predictive variables for recognition performance (which was the binomial dependent variable). Furthermore, we also included the trial number as a covariate measure.

The analyses were run on R (version 3.2.3), using the lme4 package (version lme4_1.1-7). To achieve the optimum lmer model, random slopes for all independent variables were tested incrementally for subjects and items, starting from the ‘random intercepts’-only model. The best model fit was obtained with ‘overlap’ and ‘recognition’ probe as independent variables. This model was run with the settings for a binomial dependent measure, and included a random intercept across participants and items, and a random slope for the recognition probe across participants. P-values were determined based on the z-values within the glmer model. The data files and the R scripts can be found on http://opensciencefamework.org/profile/v49bp.

RESULTS

Table 1 provides an overview of the recognition performance of all probe types across the different sentence conditions. Overall accuracy on the probe recognition task was 63%. There were 68% correct recognitions for ‘between probes’, 74% correct recognitions for ‘within probes’, but only 48% correct rejections for ‘foils’. The d’ scores were 0.59 for the ‘within probes’ and 0.41 for the ‘between probes’, respectively. According to the best fit model reported above, there were more correct responses to the ‘within probes’ and ‘between probes’ (i.e., hits) on average, than to the foils (i.e., correct rejections): (β = -0.775, z = -5.856, Pr (>|z|) < .001). The low number of correct rejections of foils likely results from ordering errors, as foils consisted of pitches that were presented in the pitch sequence but in the reversed order. The difference in ‘within probe’ and ‘between probe’ performance was also significant (β = -0.253, z = -3.113, Pr (>|z|) = .002), which clearly demonstrates that in general, phrase boundaries were processed. Regarding the trial progression, a small, non-significant increase in correct probe recognition (between and within-probes) as compared to foil performance could be observed.

Probe condition	**Control**	**‘Out-of-context’ Violation Overlap**	**‘Out-of-context’ Violation No Overlap**	**‘Garden path’ Unexpectancy Overlap**	**‘Garden Path’ Unexpectancy No Overlap**
Within	73.74% *75.32%* *(6.51%)*	73.75% *75.34%* *(8.58%)*	79.37% *81.01%* *(7.82%)*	67.50% *68.90%* *(9.16%)*	78.75% *80.33%* *(7.90%)*
Between	66.40% *68.57%* *(7.98%)*	66.88% *69.07%* *(9.89%)*	68.13% *70.36%* *(9.76%)*	76.25% *78.79%* *(8.70%)*	70.00% *72.39%* *(9.57%)*
Foil	47.34% *47.11%* *(6.79%)*	50.00% *49.90%* *(9.08%)*	50.63% *50.53%* *(9.11%)*	50.00% *49.88%* *(9.09%)*	47.50% *47.29%* *(8.98%)*

Table 1: Overview of the numerical differences in recognition performance across recognition probe, sentence condition, and unexpectancy/boundary overlap. In italics, the respective percentages are displayed as modelled by the best fit model, for which the distances to the 95% confidence boundaries are mentioned between brackets.

Importantly, there was a significant interaction between how much the ‘within probe’ performance differed from the ‘between probe’ performance and whether or not a sentential unexpectancy was presented simultaneously with the structural shift in the music. In line with a BPE, the advantage for ‘within probes’ over ‘between probes’ was stronger when there was no overlap between the pitch boundary and an unexpected sentence segment (β = 0.230, z = 2.526, Pr (>|z|) = .012). There was no significant difference in ‘foil’ probe performance when contrasting ‘overlap’ to ‘no overlap’ conditions.

Although ‘sentence type’ in general did not significantly improve the fit of the lmer model, it remains important to our theoretical hypothesis to look at the three-way interaction between overlap condition (‘overlap’/ ‘no overlap’), probe type (‘within’/ ‘between’/ ‘foil’) and sentence condition (‘control’ / ‘out of context’ violation / ‘garden path’ unexpectancy). Therefore, we ran the lmer model including sentence type as an independent variable. This model showed the general ‘within probe’ advantage (β = -0.249, z = -2.420, Pr (>|z|) = .016). However, the three way interaction between probe type, overlap and sentence type did not approach significance (β = 0.322, z = 1.423, Pr (>|z|) = .155). Nevertheless, it is important to acknowledge that the overlap*condition interaction includes 5 out of 6 cells in which no difference in the ‘within probe’ advantage is expected or found. Though it is perfectly in line with our hypotheses to only find a decreased ‘within probe’ advantage in the ‘garden path /overlap’ conditions, this imbalance between critical and control conditions may have seriously reduced the power of the three-way interaction.

Using simple contrasts, we do find that the ‘within probe’ advantage is significantly smaller for the ‘garden path/overlap’ condition as compared to all five other conditions: ‘overlap/control’ (β = 0.350 , z = 2.215 , Pr(>|z|) = .027), ‘overlap/out of context’ (β = 0.411 , z = 2.269 , Pr(>|z|) = .023), ‘no overlap/control’ (β = 0.507 , z = 3.195 , Pr(>|z|) = .001), ‘no overlap /garden path’ (β = 0.492 , z = 2.593 , Pr(>|z|) = .010), ‘no overlap /out of context’ (β = 0.562 , z = 2.992 , Pr(>|z|) = .003). Furthermore, the ‘within probe’ advantage was not significantly different when comparing any of the other conditions with each other. Given that the data pattern thus follows our expected pattern and that the ‘garden path/overlap’ condition shows significant differences in the 'within probe' advantage as compared to all other conditions, we decided to further split up the data to investigate these effects.

Within the 'no overlap' data there was a significant 'within probe' advantage ($\beta = -0.263$, $z = -2.584$, Pr (>|z|) = .010). Furthermore, there was a significantly lower performance for foil probes ($\beta = -0.741$, $z = -4.885$, Pr (>|z|) < .001) as compared to 'within probes' and 'between probes'. However, no significant interaction with sentence type was present, as expected.

Within the 'overlap' data, we found a significantly lower performance for foil probes ($\beta = -0.661$, $z = -4.462$, Pr (>|z|) < .001). Importantly, we also found an interaction between sentence type and probe type ($\beta = 0.343$, $z = 2.188$, Pr (>|z|) = .029). More specifically, sentences containing a garden path unexpectancy had a poorer performance on 'within probe' recognition and a higher performance on 'between probe' trials as compared to the other sentence conditions in our 'overlap' data, resulting in a strongly decreased 'within probe' advantage to the point of a small 'within probe' disadvantage.

Figure 6 illustrates the differential recognition performance, specifically in the condition where a structural shift in the pitch sequence co-occurred with a garden path unexpectancy in the sentence (see Table 1).

It is important to note that, although we did hypothesize a BPE when comparing all other conditions to the 'overlap/garden path condition', we did not a priori hypothesize that there would be a 'within probe' disadvantage in the 'overlap/garden path condition' (see Figure 7). Rather, based on the assumption that the pitch sequence would not be structurally integrated, a similar performance for 'within probes' and 'between probes' performance might have been expected. Given that the 'within probe' disadvantage was not expected and is not significant by conventional standards (although admittedly close to it, $\beta = 0.271$, $z = 1.903$, Pr (>|z|) = .06), we will refrain from extensive speculation about any reasons for it. As illustrated in Figure 7, there might be a slight 'baseline' preference in our stimuli, so that when there is no structural processing at all, there is a slight 'between probe' advantage. For the goals of the current study, it is more important to have established a BPE in those conditions where we expected it.

Finally, it is important to acknowledge that the amount of formal musical training of the participants did not significantly affect recognition performance, as can be expected given the novelty of our experimentally manipulated pitch sequences. This lack of an expertise effect suggests that the structures could not easily be recognized in an explicit manner. Table 2 shows how the amount of formal training of the participants relates to the performance on the recognition task. Though there is a slight indication for the 'within probe' advantage to increase alongside years of formal musical training, this is far from significant.

Figure 6: Graphic representation of the differences in 'within probe' as compared to 'between probe' performance, referred to as the 'within probe' advantage, in the several sentence conditions, when the sentential unexpectancies do or do not overlap. As suggested by the 95% confidence intervals plotted for every condition, there is a significantly lower 'within probe' advantage only when a linguistic overlap that requires reintegration overlaps with the pitch boundary.

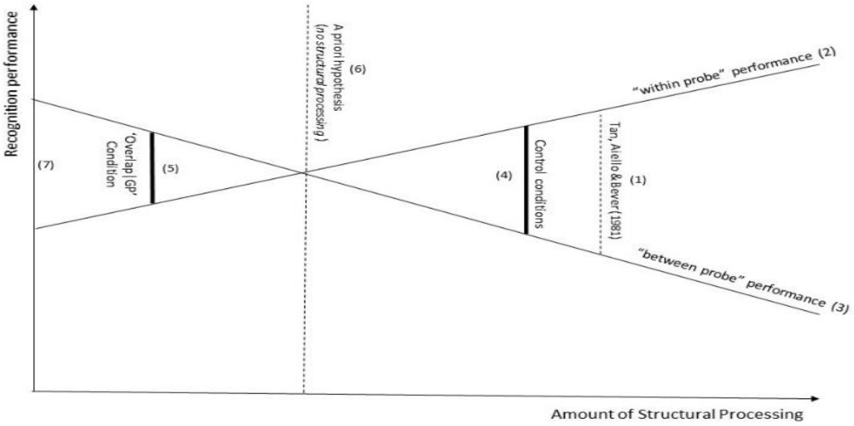

Figure 7: Graphic representation of the BPE and the expected and found results. Based on Tan et al.'s finding (1981) that 'within probes' are recognized better as sequentially occurring than 'between probes' (1), it has been argued that this pattern of results might stem form an increase of 'within probe' performance (2) and a decrease of 'between probe' performance (3) following a more parsed representation of the tone sequence , due to structural processing. Given this pattern of decrease and increase (which we call the BPE), we would also expect that all conditions where we did not attempt to induce an interference in structural processing resources (4) would have a higher 'within probe' performance and a lower 'between probe' performance, compared to our 'overlap/garden path' condition (5), where we did induce an interference in structural processing resources across domains. Interestingly, where we would have expected this trend to go no further than an even performance on both kinds of probes (6), we find that, when structural processing resources are depleted, we observe a 'between probe' advantage. This seems to suggest (7) that 'between probes' might, in situations where relatively little structural processing takes place, actually be recognized better as compared to 'within probes.

Years of Formal Training	**0**	**2**	**4**	**6**	**8**	**10**
Within	*73.54%* *(5.63%)*	*75.32%* *(4.46%)*	*77.02%* *(4.55%)*	*78.63%* *(5.62%)*	*80.16%* *(7.14%)*	*81.61%* *(8.81%)*
Between	*70.91%* *(7.39%)*	*70.70%* *(6.08%)*	*70.49%* *(6.40%)*	*70.28%* *(8.20%)*	*70.07%* *(10.88%)*	*69.85%* *(14.01%)*
Foil	*47.83%* *(5.46%)*	*48.15%* *(4.55%)*	*48.46%* *(4.76%)*	*48.77%* *(5.97%)*	*49.09%* *(7.70%)*	*(49.41%)* *(9.86%)*

Table 2: Overview of the probe recognition performance by years of formal training, as modelled using the best model fit. For each averaged percentage, the distance to the 95% confidence interval is listed in brackets.

DISCUSSION

The goal of the current study was to provide a new test of the hypothesis that there is an overlap in resources for structure processing across domains (Kljajevic, 2010; Slevc et al., 2009). Whereas previous research has mostly directly investigated this claim by addressing the interference of non-linguistic manipulations on syntactic processing in language, some doubt has been cast on whether the nature of the interference is syntactic (Perruchet & Poulin-Charronnat, 2013). Therefore, we developed a novel paradigm in which the influence of sentential syntax processing on the structural processing of basic pitch sequences was investigated.

Using a dual task paradigm, we provided sentences containing reintegratable and non-reintegratable unexpectancies simultaneously with pitch sequences that entailed a cluster shift. We found a BPE (which is an indication for stronger structural processing of the pitch sequence) when comparing sentences containing no unexpectancy or an ‘out-of-context’ unexpectancy simultaneously with the pitch boundary to sentences containing a ‘garden path’ unexpectancy simultaneously with the pitch boundary. The BPE thus indicates that, specifically when the pitch boundary was matched to a sentential unexpectancy that required structural reintegration, there was a weaker structural processing of this pitch boundary.

These findings provide suggestive evidence in favour of models (Patel, 2003) which state that the integrational resources that are required in the structural processing of linguistic and non-linguistic materials are shared between the two domains. As we found interference between structural processing in linguistic and non-linguistic domains on the basis of syntactic garden paths, but not word category violations, this does suggest an interpretation beyond syntactic processing resources to structural reintegration resources. This is in line with the recent findings by Perruchet and Poulin-Charronnat (2013), where interference effects found were also dependent on whether or not the sentential unexpectancies invoked structural reintegration.

We admit that the finding of a small numerical ‘within probe’ disadvantage in the condition where no structural processing was argued to occur, is rather unexpected. As this difference did not reach significance, it may be reflect nothing more than noise in our data. However, assuming there is really such a within probe disadvantage, how can we explain a baseline level where, without structural processing, there is a better performance for ‘between probes’ versus ‘within probes’ performance, when the structure of the pitch sequence is not processed? One might argue that the ‘between phrase’ tones have a higher saliency than the ‘within phrase’ tones, even if the pitch sequence is not structurally processed. A reason for this might be that these ‘between phrase’ transitions draw more attentional resources based on the pitch cluster transition between the novel and preceding tone. After all, an implicit learning of the pitch clusters would lead participants to expect a within-cluster continuation of the preceding tone. Such an explanation would thus make a distinction between the levels of structural detection and structural reintegration of the pitch boundary, which might pose an interesting subject for future research.

Accounts of resource interference

Importantly, our demonstration of cross-domain interference in structural processing has theoretical implications that go beyond the confirmation of a prediction from the SSIRH (Patel, 2003). In particular, the findings are relevant for a recent debate concerning the resources underlying previously found interference effects (Perruchet & Poulin-Charronnat, 2013; Slevc et al., 2009). As mentioned in the introduction, Perruchet and Poulin-Charronnat recently conducted an experiment with a version of Slevc et al.’s paradigm, using semantic garden path sentences as opposed to simple semantic violations (e.g., *‘the old man went to the bank to withdraw his NET* *which was empty'*). Slevc et al. reported that musical unexpectancies increased the effect of syntactic garden path unexpectancies on reading times, but did not modulate the effect of semantic violations. However, Perruchet and Poulin-Charronnat did find a modulation of a semantic effect, namely of semantic garden path unexpectancies (where a reintegration is possible). It thus seems that the type of linguistic unexpectancy (garden path configuration as opposed to a violation) determines the occurrence of music-to-language interference rather than the linguistic level of the unexpectancy (syntax vs. semantics, Koelsch, 2005, Rohrmeier & Koelsch, 2012), which might suggest a broad interpretation of Patel's definition of 'structural integration resources' as being dependency-based processing resources for instance.

However, based on their finding of modulation effects on semantic garden path sentences, Perruchet and Poulin-Charronnat (2013) have suggested that attentional aspects of the task might be implied. Perruchet and Poulin-Charronnat reasoned that the amount of attentional resources spent on the musical part of the interference study varies as a function of the structural expectancy of the materials. They suggest that the musical unexpectancies might have different consequences for garden path sentences than for sentences with sentential unexpectancies because of differences in the attentional constraints of the sentential unexpectancies in both conditions. Whereas garden path unexpectancies are resolved as soon as the right integrational structure is found, the violations cannot be resolved. Therefore, it can be argued that garden path unexpectancies require moderate amounts of attentional resources and can thus be hindered by the depletion of attentional resources towards structural unexpectancies. Full sentential violations, on the other hand, have a much stronger demand towards the attentional resources, and thus force the participant to disregard the musical task demands.

This claim of an attentional basis for overlapping resources proved difficult to assess in previous research, given that it has only used linguistic or electrophysiological measures of structural integration. On these general measures, the hypotheses of attentional demands and structural integration demands are difficult to disentangle (e.g., both predict longer reading times).

However, this is not the case in the novel dependent measure used here. As mentioned above, the structural integration effect in the pitch recognition task is expressed as a memory effect: if a shift is processed more strongly, the sequence of the tones spanning this shift is remembered less well, and vice versa. In other words, if we observe a decrease in the BPE (as we find upon simultaneous presentation of a garden path unexpectancy with the pitch cluster shift), it must be noted that this decrease is in part due to a better performance for 'between phrase' tones in this condition as compared to the control conditions. In other words, upon the joint presentation of the garden path unexpectancy with a pitch cluster shift, the pitches spanning the shift are recognized better ($\beta = 0.492$, $z = 2.112$, $Pr (>|z|) = .034$). Of course, this clearly contrasts with the attentional hypothesis, which would state that the sequence of tones presented simultaneously with the garden path unexpectancy will be attended less, and thus also recognized less well, as compared control conditions. This is clear from Table 1, where our data show an increased instead of a decreased performance on 'between probe' recognition in this condition.

Therefore, the findings reported above do not only provide first evidence for cross-domain interference in structural integration resources involved in 'default' structural integration, but furthermore argue against the account of such interference being attentional in nature. While the experimental nature of the pitch clustering allowed for a more controlled task environment, we believe future work would make an important contribution to the research domain if it applied the abovementioned procedure to more naturalistic, harmonically organized pitch sequences, specifically investigating the domain of harmonic musical processing. For now however, the study suggests that measuring the structural processing of non-linguistic auditory sequences is both possible, and reveals interference effects with simultaneous sentential processing.

CONCLUSION

This study provides the first evidence for interference from the simultaneous processing of linguistic structure upon the structural processing of structured pitch sequences. Thereby, it uniquely provides evidence for models suggesting an overlap in structural processing resources (SSIRH, Patel, 2003; SWM, Kljajevic, 2010) by using a measure of 'default' structural processing in non-linguistic materials. Additionally, this measure further allows us to address a recent point of discussion concerning such 'shared resource'-models, namely the attentional account as provided by Perruchet and Poulin-Charronnat (2013). Though earlier findings of interference between domains can be accounted for as an effect of depletion of attentional rather than integrational resources, the findings reported in this study enable us to discriminate between the two, providing clear evidence in favour of overlapping integrational measures. Therefore, we suggest that the findings reported in our, as well as in previous (Perruchet & Poulin-Charronnat, 2013; Slevc. et al, 2009) studies, suggest shared integrational resources.

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CHAPTER 3

ELECTROPHYSIOLOGICAL SUPPORT FOR INTERACTIONS DURING THE JOINT STRUCTURAL PROCESSING OF LINGUISTIC AND NON-LINGUISTIC MATERIALS [1]

In support of recent models (Kljajevic, 2010) claiming domain-generality of structural processing resources, several studies have found interactions across content domains such as music, language, and action when participants encounter structural difficulties in both domains at the same time. However, the simultaneous presentation of structural difficulties is highly unnaturalistic, and makes a direct interpretation of previously found interactions effects difficult. Therefore, the current study asked whether there is overlap in structural processing of linguistic and non-linguistic materials, even when the materials contained no structural difficulties. To do so, we manipulated structural contingencies between domains, so that a particular structure in one domain became predictive of an analogous structure in another domain. Specifically, in the current EEG study, participants performed a joint processing task in which they read sentences while listening to pitch sequences. Both materials were structurally sound, and structural congruency was manipulated so that the sentential disambiguation would follow the attachment structure of the (earlier disambiguated) pitch sequence in 80% of trials. A sentence comprehension task and pitch recognition task performed after every trial showed an accurate and attentive processing of all materials. An analysis of event-related potentials, time-locked to the point of structural disambiguation of the sentence (where the two attachment structures turned out to be congruent or incongruent) revealed several event-related potentials related to (structural) unexpectancy processing (P2, eLAN, P3, LAN, P6) when the sentential attachment structure was incongruent with that of the pitch sequence. This suggests that, either through a sharedness of structural prediction mechanisms or a more general implicit learning of the structural contingency, participants were sensitive to our manipulation and formed structural predictions across domains.

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[1] Van de Cavey, J., Kourtis, D., & Hartsuiker, R.J. (submitted). Structural Processing across Domains: electrophysiological support for interactions during the joint structural processing of linguistic and non-linguistic materials.

INTRODUCTION

In several domains (e.g., music, language, math, action), the structural processing of sequential information is a key requirement for our daily functioning. This overlap in structural processing requirements is reflected in commonalities between structural processing models across domains (e.g., Generative Theory of Tonal Music, Lerdahl & Jackendoff, 1983; Dependency Locality Theory, Gibson, 2000). The structural processing of both linguistic and musical materials involves dependency processing (e.g., whether a tone is in key or out of key) which is based upon (usually implicit) knowledge about regularities that are stored in long-term memory (for a review, see Koelsch, 2009). And similar to linguistic processing, the processing of music is largely guided by the creation (and violation) of expectancies on the basis of these regularities (e.g., Perruchet, 2008).

Given these similarities, it is not surprising that over the past decade, several models (e.g., Shared Syntactic Integration Resource Hypothesis, Patel, 2008; Syntactic Working Memory, Kljajevic, 2010) have theorized that resources supporting structural processing are shared across content domains. Whereas syntactic rule representations are of course distinct between domains, structural processing across domains might still show overlap because structural processing mechanisms make a demand on a domain-general set of resources. In support of such models, several studies do indeed find that providing structural processing difficulties simultaneously in the linguistic and non-linguistic domains causes interference.

For example, Slevc, Rosenberg, and Patel (2009) found that the simultaneous presentation of a harmonically unexpected chord increased the reading time slowing of syntactic ‘garden path’ unexpectancies in sentences, but not the reading time slowing of semantic errors in sentences. These findings thus suggest that the joint processing of structural integration unexpectancies in both linguistic and non-linguistic materials causes competition for shared *structural* processing resources and thus interference. Similarly, Koelsch, Gunter, Wittfoth and Sammler (2005) investigated event-related potentials (more specifically, the left anterior negativity or LAN) related to the processing of syntactic difficulties, when the sentences containing such difficulties were presented in combination with musical sequences. They found that the LAN was significantly reduced when a harmonically unexpected chord was presented together with the syntactic difficulty in the sentences.

These findings of interactions in structural processing across domains are also in line with the similarity in the event-related potentials that are typically elicited in the processing of difficulties in linguistic syntax or musical harmony. In both domains, the processing of such difficulties has been often linked to an early negativity in frontal regions, around 100-300 ms after presentation of a structural difficulty. In language, this early negativity is most commonly known as early left anterior negativity (eLAN), which has been reported by Friederici (2002) during the study of phrase structure violations, and has been repeatedly found for structural violations. The eLAN's most prominent neural source is the left anterior region (Jentschke & Koelsch, 2009). In music, the processing of harmonic difficulties is linked to a similar negativity, which is typically found over the right hemisphere (eRAN). The eRAN is considered to reflect difficulties in the harmonic integration of incoming elements with the preceding tonal context. The eRAN (see Koelsch, 2012), has for example been found when participants listened to melodies that contained Neapolitan chords instead of harmonically appropriate chords (e.g., Steinbeis & Koelsch, 2008). Therefore, in analogy to the linguistic eLAN, the eRAN is taken as a reflection of a violation of the participant's structural expectancy (Koelsch, 2012). Not only are these early negative components similar across language and music (aside from their lateralization), but some interactions between the two domains have also been found on these components. For example, Jentschke and Koelsch (2009) found that when presenting young children with sentences containing syntactic errors (where a preposition was not followed by a noun), an eLAN could be found, the amplitude of which varied with the musical training of those children.

Furthermore, the processing of structural difficulties in linguistic and non-linguistic materials is also known to evoke event-related potentials associated with attention allocation. One such a component is the P3, a positive component around 250-500 ms (Polich, 2007), which is taken to reflect attention allocation and decision making. It typically contains frontal and central electrodes at first (P3a), linked to the engagement of attention and novelty processing (Polich, 2003), followed later by a more parietal component (P3b) depending on the improbability of the event for task-related processing (Polich, 2003). The P3 has been related to the provision of structurally unexpected elements (Regnault, Bigand & Besson, 2001), and is often seen as a precursor of later structural reintegration components.

These later structural reintegration components can be somewhat differentiated across language and music, but also contain several forms of overlap. In language, the most well-known structural reintegration component elicited by structural unexpectancies is the P600. The P600 is a positive component, typically peaking around 600 ms (Friederici, 2002; Friederici & Weissenborn, 2007), and varies in distribution: a posterior distribution across the scalp is more often related to repair and revision of syntactic errors, whereas a frontally distributed positivity relates to ambiguity resolution or an increase in discourse complexity (see Kaan & Swaab, 2003). Though the P600 is typically discussed in the study of linguistic syntax processing, the P600 can also be found for harmonic unexpectancies (Patel, Gibson, Ratner, Besson, & Holcomb, 1998). Therefore, it is sometimes referred to as a ‘structural reintegration’ component (Friederici, 2002).

The late positivity (P600) related to structural integration in both language and music is often preceded by a late negative component. In music perception research, this late right anterior negativity component has been termed the N5. The N5 is a broad, late negativity, found typically between 500-800 ms with an anterior distribution, commonly with a right lateralization. The N5 is suggested to reflect processes of harmonic integration (Poulin-Charronnat, Bigand, & Koelsch, 2006), typically occurring when a listener’s representation of the preceding melodic harmony needs to be modified (e.g., Koelsch, 2012; Steinbeis & Koelsch, 2008). In psycholinguistic research, several ERP studies (e.g., Friederici, 2002; Steinbeis & Koelsch, 2008) have reported a linguistic late left anterior negativity, the LAN. The LAN is a negative component ranging from 300-700 ms, and is associated with the structural processing of function words (i.e., words which have a key role in structural parsing, rather than semantic context). Function word processing for example has consistently been shown to elicit this LAN effect.

In summary, the overlap in neurodevelopmental findings for both linguistic and non-linguistic materials supports ‘resource sharing’ models in their assumption that structural processing across content domains might be based on overlapping resources (SSIRH, Patel, 2003; SWM, Kljajevic, 2010). This has been supported by studies showing interference during the joint processing of structural difficulties across materials, both behaviourally and neurophysiologically (e.g., Slevc et al., 2009). Furthermore, EEG studies have shown some strong parallels when investigating the processing of structural difficulties in linguistic and non-linguistic materials; in both domains, such processing is characterized by early (eLAN or eRAN) and late (LAN or N5) negativities, and a late positive component (P600).

Nevertheless, the hypothesis that language and music processing make a demand on shared resources has recently been strongly debated (Slevc & Okada, 2015). After all, it is important to keep in mind that these interference effects and event-related potentials, both in within-domain and in cross-domain studies, have been elicited by the simultaneous provision of structural unexpectancies in materials. A paradigm that provides strong within-material unexpectancies simultaneously, creates possible confounds in terms of attentional processing and general conflict monitoring (see Perruchet & Poulin-Charronnat, 2013). Furthermore, the prolific use of such difficulties leads to experimental paradigms which are, in any case, highly unnaturalistic events. After all, while the joint processing of structured materials (such as language, music, or action) happens quite frequently during our daily activities, these materials are usually structurally sound, and structural disambiguations in both materials are very rarely presented simultaneously.

An interesting perspective on this debate would be to examine the extent to which interactions in event-related potentials referring to structural processing across domains can be elicited using well-structured materials. Therefore, we investigated to what extent interactions in structural processing across domains might be elicited through a manipulation of structural predictions *across* domains, rather than the provision of structural unexpectancies *within* domains.

Current study

In the current ERP study, we provided participants with simple pitch sequences while they read sentences that contained a relative clause. The materials in both domains were structurally sound, but were ambiguous with respect to their integrational structure: in the sentences, the relative clause could attach to either the first or the second of two noun phrases and in the pitch sequence, the final pitches could either continue the previous part of the sequence or an earlier one (see below). The integrational structure of the sentences was always disambiguated after the boundary structure of the pitch sequences was determined. This entails that, in contrast to earlier joint processing studies (e.g., Koelsch et al., 2005), there could be no interaction of structural difficulties within both materials. However, based on earlier findings of cross-domain continuation of preferences during the processing of sequences in several cognitive domains (Scheepers, Sturt, Martin, Myachykov, Teevan & Viskupova, 2011; Scheepers & Sturt, 2014), we hypothesized that participants could be sensitive to interactions between the attachment structures in both materials.

To elicit these interactions, we provided a contingency between the dependency structure of the pitch sequences and the subsequently disambiguated attachment structure of the sentences. In 80% of trials, a long dependency in the pitch sequence structure would be followed by a long dependency in the sentence too (i.e., a high attachment of the relative clause in the sentence) and respectively, a short dependency in the pitch sequence structure would be followed by a short dependency in the sentence (i.e., a low attachment of the relative clause in the sentence). In 20% of the trials, this contingency was violated (e.g., a pitch sequence containing a high attachment followed by a low attachment relative clause). After the joint presentation of sentences and pitch sequences, participants were provided with a comprehension question concerning the sentence, and a recognition task concerning the pitch sequence, to ensure attentive processing of both materials, as well as to and control for differences in difficulty of general processing across conditions.

We measured event-related potentials, which were time-locked to the disambiguation of the sentence. With these event-related potentials, we tested our hypothesis that processing of the sentential disambiguations would interact with our contingency manipulation: a sentential disambiguation might become less expected on the basis of a previously processed pitch sequence structure.

METHOD

Participants

We tested 24 participants from the Ghent University student pool (24 years of age on average; 8 male, 16 female participants). All participants were native speakers of Dutch; they participated in exchange for a monetary compensation. Participants were not required to have any musical training, and they filled in questionnaires concerning their musical expertise, the results of which were included as covariates in our analysis. Before data processing, one participant was removed because of technical issues. All participants were right-handed, and reported no reading (sight, dyslexia) or hearing difficulties.

Materials

Sentences. We constructed 160 relative clause sentences in Dutch. Half of these sentences contained a relative clause with a high attachment construction (e.g., *'De soldaat bekijkt de map van de wegen die versleten is'*, translated word for word as ‘the soldier looks at the map of the roads that [worn out IS]’). The other half of these sentences contained a relative clause with a low attachment construction (e.g., *‘De soldaat bekijkt de map van de wegen die versleten zijn'*, translated word for word as ‘the soldier looks at the map of the roads that [worn out ARE]’).

Importantly, the attachment structure was always disambiguated at the last word, which was the auxiliary verb, by making this verb plural or singular (*‘is’/’zijn’*, translated as ‘is’/’are’). Within each attachment structure, half of the verbs were plural and half were singular. Also, there were as many sentences with the first noun phrase being plural as there were with the second noun phrase being plural. The number of the verb presented at the end of a specific sentence was counterbalanced across participants.

Pitch Sequences. We created pitch sequences to either match or mismatch the integrational structure of high and low attachment relative clause sentences. This was done by following the procedure described in Van de Cavey and Hartsuiker (2016). The pitch sequences consisted of 8 pitches, with a duration of 370 ms each and with 200 ms silences separating adjacent pitches. Their frequencies ranged from 196.00 to 698.46 Hz and corresponded to 18 tones: G, Ab, A, B, (middle) C, Db, Eb, E, F, and the same tones repeated over the fifth octave. To create an experimental phrasing structure, we organized these tones into three clusters: ‘A-E-B’, ‘F-C-G’, and ‘Ab-Eb-Db’. These tone clusters were chosen so that tones within each cluster would be close harmonic neighbours, but the clusters would not follow Western Tonal Harmony (which might evoke explicit processing of the tone sequences).

By varying tone transitions within and between clusters, we manipulated the integrational structure of the pitch sequences. In all our pitch sequences, the first pitch was randomly selected from our 18 tones, and the second and third pitch were selected to each be a neighbour of the preceding tone within the same pitch cluster. However, the fourth tone was again randomly selected outside of the pitch cluster of the third tone. Therefore, the tone transition from third to fourth pitch always entailed a cluster boundary. The fifth and sixth tones were again selected to each be a neighbour of the preceding tone within the same pitch cluster.

For half of our pitch sequences, there was a cluster shift between the sixth and seventh tone, where the seventh tone was selected randomly from the same cluster as the first three tones, and the eight tone was a within-cluster neighbour of the seventh tone. Thus, in this half of the pitch sequences, a high attachment was created in the pitch sequence structure, where the pitch sequence end (7th and 8th tone) completed the root of the pitch sequence (1st to 3rd tone). For the other half of our pitch sequences, there was no cluster shift between the sixth and seventh tone. However, to match for superficial frequency transitions induced by a cluster shift, the seventh tone was selected randomly, but within the pitch cluster of the sixth tone. On average, this creates a frequency shift which is similar or even exceeds that of a structural boundary, but it entails no pitch cluster shift. In other words, in this half of the pitch sequences, a low attachment was created, where the pitch sequence end (7th and 8th tone) was a continuation of the preceding cluster (4th to 6th tone). An overview is presented in Figure 1.
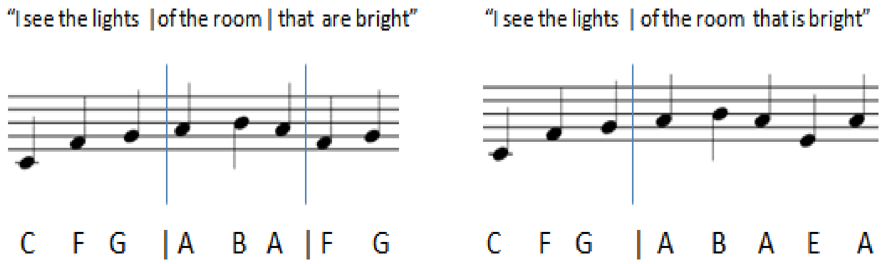
Figure 1: Overview of the high (left frame) and low (right frame) attachment structures in our sentences and pitch sequences. In the sentences, the attachment manipulation was made by changing the final verb (is/are), thereby changing the attachment of the relative clause. In the pitch sequences, the attachment manipulation was made by presenting a pitch cluster boundary (represented by a blue line) between the 6th and 7th tone for high attachment structure going back to the root of the pitch sequence.

Importantly, we ensured that there was a contingency between the structure of the pitch sequence (i.e., whether or not the cluster structure of the pitch sequence contained a high attachment) and the attachment structure of the accompanying sentence (high or low attachment of the relative clause). For the 160 trials, the attachment structure of the sentences was matched with that of the pitch sequences so that both would be congruent (HA-HA or LA-LA) in 80% of the cases, and would be incongruent (HA-LA) or (LA-HA) in 20% of the cases. Importantly, the attachment structure of the pitch sequence is disambiguated between the 6th and 7th pitch. The attachment structure of the sentence is disambiguated later, at the last sentence segment containing the verb.

Dependent Measures

Behavioural measure of pitch sequence processing. To assure that participants were listening attentively to the pitch sequences, each joint presentation of a sentence and pitch sequence was followed by a recognition task in which participants were asked whether a pitch pair had also been presented in the previously heard pitch sequence (in that sequential order).

In addition to promoting attentive listening, this recognition task also functioned as a test for the structural processing of the pitch boundaries within the non-linguistic sequences (see Van de Cavey & Hartsuiker, 2016). Tan, Aiello, and Bever (1981) used the same recognition task and found that participants were significantly worse at recognizing a tone pair presented in a melody when this pair spanned a harmonic boundary, as compared to when it did not. This advantage for recognition probes consisting of pairs within a harmonic segment (called ‘within probes’) as compared to recognition probes referring to pairs spanning two harmonic segments (called ‘between probes’) was taken by Van de Cavey and Hartsuiker (2016) as an indication that the harmonic boundary had indeed been processed by the participant. In our recognition task as well, we have used this ‘within probe’ advantage effect to check to what extent our pitch cluster boundaries were processed by the participants.

On 1/3 of the trials, the probe that was used for the pitch recognition task would be a foil consisting of two pitches that were presented in the preceding pitch sequence, but not in that order, and thus would warrant no-response. Importantly, of the 2/3 remaining trials, which had a correct recognition probe, half of the probes would refer to a ‘within phrase’ part of the preceding pitch sequence, and half of these probes would refer to a ‘between phrase’ part of the preceding pitch sequence. This way, not only the general processing of the pitch sequence, but also the processing of its integrational structure, could be measured.

Behavioural measure of sentence processing. To control for attentive processing of the sentences, a content question was asked after the presentation of the pitch recognition task. This content question related to the attachment structure of the sentence (e.g., *'I see the kids of the woman who is tired'* would be followed by a content question like *'are the kids tired?'*) Participants were required to respond with 'yes' or 'no', and results were included in the analysis.

Procedure

The participants performed 160 trials, with each trial consisting of a joint presentation of a sentence and a pitch sequence, followed by a pitch recognition task and a sentence comprehension task. After a fixation cross (500ms) and a black screen (500 ms), the 8 sentence segments were presented for 370ms, separated by 230 ms silences. With the onset of each sentence segment, the corresponding pitch was auditorily presented. For the recognition task, the background colour of the screen changed from black to blue, and participants responded to the two-pitch recognition probe that was provided by pressing 'f' or 'j' for wrong or right, respectively. After completing this task, a black screen was presented for one second, and then a question, measuring sentence comprehension, was presented against a blue background. Participants responded to the question by pressing 'f' or 'j' for wrong or right, respectively. We included small breaks after each ten trials, in which participants had the time to move slightly if necessary or give the experimenter notice. If everything was in order, the experimenter continued the experiment by clicking a button. In a debriefing after the experiment, none of the participants indicated to have been aware of the contingency manipulation. For an overview, see Figure 2.

Analysis

Behavioural analysis. To analyse the probe recognition performance, the independent variables 'pitch structure' (i.e., HA or LA structured pitch sequences), 'congruency' (i.e., whether the final sentence segment revealed the expected congruency between sentence and pitch structure or not), and ‘probe’ (i.e., the kind of recognition probe: ‘within’, ‘between’, or ‘foil’) were analysed in an lmer model. We thus had a 2 (‘congruency) *3 (‘probe’)*2 (‘pitch structure’) model.The behavioural data (i.e., recognition probe judgments) were analysed using a linear mixed effects model implemented in R (version 3.2.3) using the lme4 package (version lme4_1.1-7) with subjects and target sequences as crossed random factors.

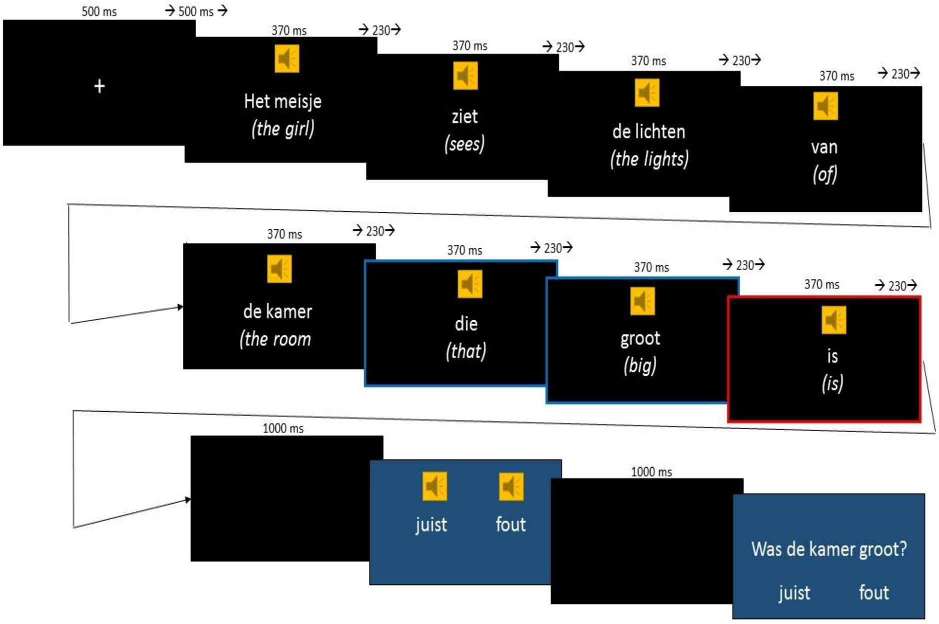

Figure 2: Overview of the procedure used in the EEG study. Participants were presented with 8 sequential screens, portraying a sentence segment accompanied by a tone. This way, a tone sequence was presented simultaneously with the sentence. The structure of the pitch sequence was determined by whether or not there was a structural boundary between the 6th and 7th segment (blue contours). At this point, the sentence still has an ambiguous structure. On the 8th segment (red contour), the final verb (*‘is’* or *‘are’*) is presented and the sentential structure is disambiguated. The EEG measurements were time-locked to the onset of this 8th segment. In 80% of trials, the attachment structure of the sentence was congruent with the previously disambiguated pitch sequence. After the joint presentation, participants judged whether a two tone recognition probe was present in the presented pitch sequence (*‘juist’* or *‘fout’* for right or wrong probe, respectively). Also, a sentence comprehension question was answered by indicating *‘juist’* or *‘fout’* for right or wrong.

For all analyses, we first defined a standard model with only random intercepts across subjects and target sequences. 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 (Bates, Kliegl, Vasishth, & Baayen, 2015). The slope of 'probe' over subject was significant. Then we incrementally determined the variables which significantly improved the lmer model. P-values were determined based on the z-values within the glmer model. The data files and the R scripts can be found on http://opensciencframework.org/profile/v49bp.

EEG Hypotheses. We hypothesized that, if participants were affected by our contingency manipulation, this might lead to structural unexpectancy effects when the sentential disambiguation mismatched the structure of the accompanying pitch sequence. After all, in 80% of trials, the sentential disambiguation followed the earlier disambiguated pitch sequence structure. If this hypothesis is correct, we might expect ERPs related to structural unexpectancy processing in language (and perhaps to a lesser extent also for the tone sequences), in trials where sentential and pitch sequence structure turned out to be incongruent.

As reviewed in the introduction, several EEG components have been typically related to the processing of structural unexpectancies in language. First, there is an early anterior negativity, left (eLAN) lateralized for the processing of structurally unexpected elements in language. Second, such unexpectancies might make a shift in attentional processing, which has been linked to a P3 component. Third, several studies have found that the presentation of a structural unexpectancy can elicit late reintegration components, such as the P600 and the LAN. In this study, we also focus on the time windows and ROIs that are linked to these event-related potentials (see below), to test the idea that participants are guided in their structural expectancies of the sentence endings by our contingency manipulations. Note that, given that our pitch sequences are previously disambiguated and are not harmonically composed, we did not expect strong right lateralized components (eRAN, N5).

It is also important to note that, given that all sentences ended with the Dutch words for either ‘is’ or ‘are’, participants might have strong contextual predictions concerning which exact word will be presented. Such situations have typically been linked to a visual P2. This is a positive event-related potential peaking around 200 ms, located around the centro-frontal electrodes. The P2 potential is related to the visual presentation of words that are unexpected on the basis of sentential constraints, and seems to occur for sentence endings that are strongly constrained (Federmeier & Kutas, 2002; Federmeier, Mai & Kutas, 2005). Hence, we might expect such a P2 component for the visual prediction of the final verb in general, followed by structural processing components (eLAN, P3, P600) when this verb mismatched what would be structurally predicted on the basis of the earlier disambiguated pitch sequence.

In sum, on the basis of previous research on structural prediction, prior hypotheses can be made concerning time windows for positivities along the midline scalp regions (P2, P3, P6), as well as time windows for early (eLAN) and late (LAN) negativities along lateral (frontal) scalp regions. These event-related potentials have been reported for structural unexpectancies in language, and might thus be observed in trials where sentential and pitch sequence structure turned out to be incongruent. In the next section, we discuss the acquisition of data and the selection of time windows and ROIs to investigate these event-related potentials.

With regards to the attachment structure of our sentential materials, we must acknowledge that any influence of structural predictions from the processing of non-linguistic materials on the structural expectations for the sentential manipulation might be moderated by linguistic structural preferences in general. With that in mind, one important remark is that in Dutch, several previous studies have already shown that LA sentence structures are vastly preferred over HA sentence structures (Desmet & Declercq, 2006). Therefore, we might expect that our contingency manipulation is more effective in evoking structural unexpectancies when the sentential disambiguation is also an infrequent structure, as opposed to when the sentential disambiguation favours the linguistically preferred and most frequently occuring structure. In terms of the current design, it could be hypothesized that an LA disambiguation after a HA melody would be less unexpected, as compared to a HA disambiguation after an LA melody.

EEG analysis. The EEG data was collected with a Biosemi ActiveTwo system (Biosemi, Amsterdam, Netherlands), using 64 Ag-AgCI scalp electrodes positioned according to the standard international 10-20 system. In addition to these scalp electrodes, we attached external electrodes to the right and left mastoid. Furthermore, we placed electrodes directly above and below the left eye to control for blinks, as well as at the side of both eyes to control for horizontal eye movements. Signals were recorded with a sampling rate of 512 Hz.

Data were processed and analysed using EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon and Luck, 2014). Data were re-referenced to the average of the right and left mastoid and a 0.1-30Hz Band pass filter was applied. All breaks were removed manually from the recordings. Moreover, ocular correction was performed by using independent component analysis (ICA). Epochs were created, locked to the onset of the disambiguating word at the end of every sentence (which always was the verb *'is'* or *'zijn'*, respectively translated as 'is' or 'are'), with a time window from -200 (for baseline correction) to 1000 ms. Automatic artefact rejection was performed on these epochs with a subsequent visual inspection to reject missed artefacts. Artefact rejection resulted in around 9.2% rejected epochs per participant.

On the basis of the ERP components under investigation, we decided upon six regions of interest, depicted in Figure 3. These regions consisted out of the left anterior region (F5, F7, FC5), the middle anterior region (F1, FCz, F2), and the right anterior region (F6, F8, FC6). On the posterior side, there is also a left posterior region (P5, P7, CP5), a right posterior region (P6, P8, CP6), and a middle posterior region (P1, Pz, P2).

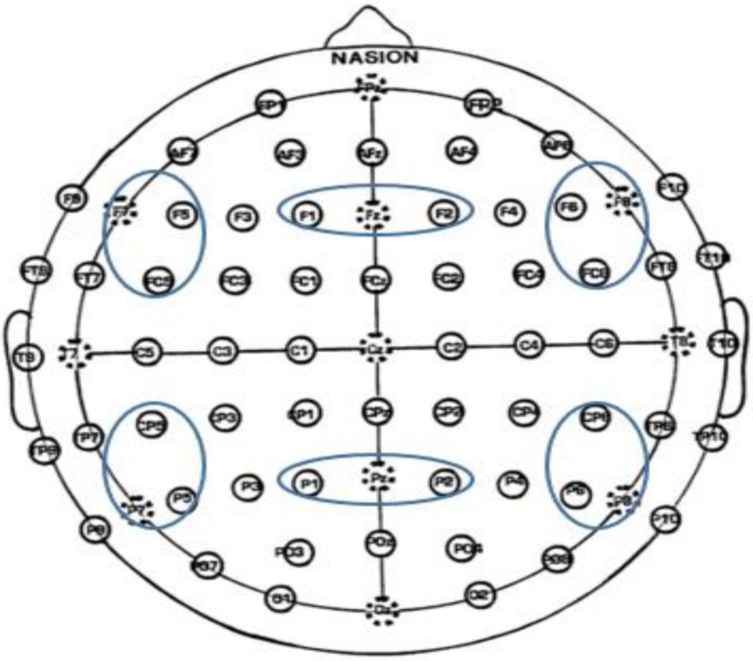

Figure 3: Overview of the six ROI's on a scalp map

Next, we determined time windows for analysis of the expected components, based on previous research studying such components in structural processing. We decided upon a time window for the early positivity (P2) based on previous studies on the P2 (Federmeier & Kutas, 2002; Federmeier, Kutas, 2009), namely 200-280 ms. For the early anterior negativity (eAN), we used a 280-340 ms time window based on time windows in previous studies investigating eLAN/eRAN (Friederici, 2002; Steinbeis & Koelsch, 2008). For the medial positive component (P3) component, we investigated the broad 300-500 ms range across posterior ROIs. For the late negative component (LAN/N5), we used a time window of 500-660 ms, based on earlier findings (Friederici, 2002). Finally, for the late positive component (P600), we used a time window of 680-740 ms for frontal regions and a time window of 580-640 ms for posterior regions, on the basis of earlier findings(Steinbeis & Koelsch, 2008; Friederici, 2002).

Importantly, based on the abovementioned research and the scalp maps plotted in Figure 4, we decided upon studying midline (frontal and posterior) ROIs for the P2, P3, and P600 components. Furthermore, we decided upon studying the left lateral frontal ROI for the eLAN and LAN, and the right lateral frontal ROI for the N5. This choice of ROI can also be statistically justified, as reported in the Appendix of this chapter. To test the significance of the EEG differences following our experimental manipulation, amplitudes were analysed for each time window within the hypothesized ROI with linear mixed effects models. In the model, ‘congruency’ (congruent, incongruent) and ‘sentential structure’ (HA, LA) were added as independent variables to model mean amplitudes. The data files and the R scripts can be found on http://opensciencframework.org/profile/v49bp.

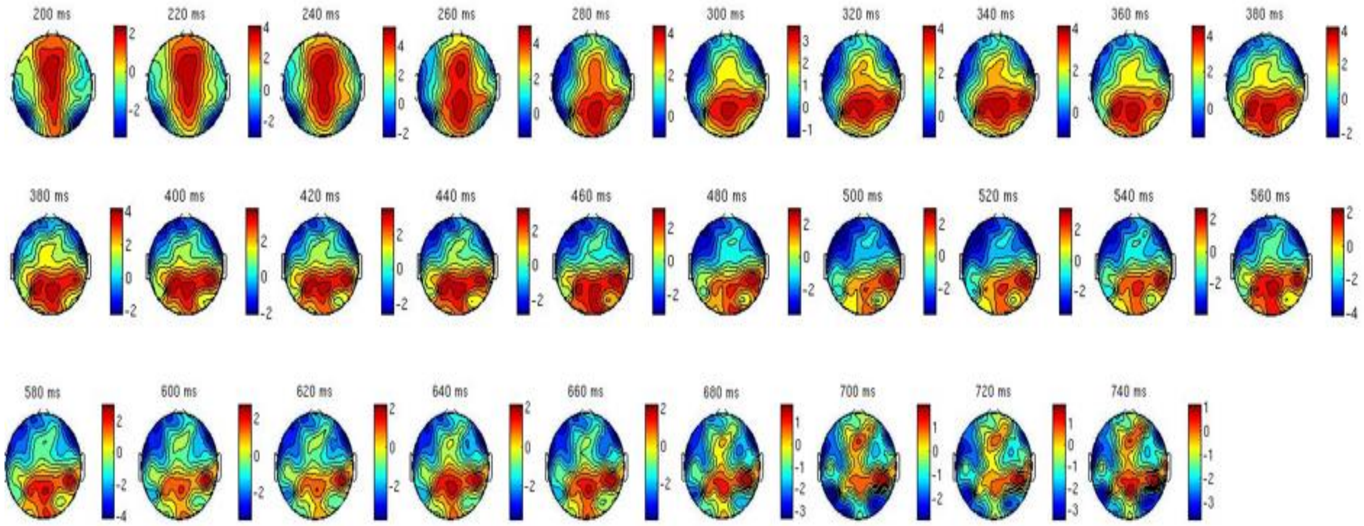

Figure 4: Overview of the scalp maps, for incongruent trials. As can be seen, positivities occur largely around the midline of the scalp map, whereas negativies are more lateralized.

RESULTS

Behavioural results

Pitch recognition task. Overall accuracy of the pitch recognition task was 60%. Importantly, there was a significant difference in recognition performance according to probe type. Recognition performance on ‘within probes’ was significantly higher ($\beta = 0.213$, $z = 2.930$, Pr (>|z|) = .003) than the recognition performance for ‘between probes’: 74% and 68% respectively. Foil probe performance was 38 %. This ‘within probe’ advantage indicates that the listeners processed the pitch boundary structure accurately. Importantly however, neither pitch sequence structure (high or low attachment) nor the congruency between the pitch structure and sentence structure revealed any differences in this ‘within probe’ advantage or general performance.

Sentence Comprehension task. The analysis of the sentence comprehension task showed an overall accuracy of 73%. There was a significant interaction between sentential dependency and verb number ($\beta = 0.953$, $z = 3.348$, Pr (>|z|) < .001), showing that participants performed better for the comprehension of LA sentences (78%) as compared to HA sentences (69%) for sentences ending with a plural verb, but participants performed worse for the comprehension of LA sentences (67%) as compared to HA sentences (78%) for sentences ending with a singular verb. However, there were no interactions between these sentential variables and our contingency manipulations.

ERP results

Below, we will report the lmer analyses for the hypothesized components (following expected time windows and ROI). The waveforms relating to these comparisons are presented in Figures 5 and 6. The statistical analysis supporting the choice of these ROIs can be found in the Appendix of this Chapter.

P2 (200-280 ms). In the middle frontal ROI, we found a significant effect of congruency: the mean amplitudes were significantly higher for incongruent trials as compared to congruent trials (β = 1.395, t= 2.496, Pr (>|z|) = .013). Moreover, there was an interaction between congruency and sentence type, showing that the abovementioned difference was significantly stronger for HA as compared to LA disambiguations (β = 1.669, t= 2.110, Pr (>|z|) = .035).

eLAN (280-340 ms). In the left frontal ROI frontal region, there was a significant effect of congruency, showing that the mean amplitudes were higher for incongruent trials (β = 1.461, t= 2.457 Pr (>|z|) = .014). Furthermore, there was a marginal interaction between congruency and sentence type, suggesting that the abovementioned effect was stronger for HA as compared to LA disambiguation (β = 1.436, t= 1.709, Pr (>|z|) = .087).

P3 (300-500 ms). In the middle posterior ROI, there was a significant effect of congruency, showing that the mean amplitudes were significantly higher for incongruent trials as compared to congruent trials (β = 1.154, t= 2.262, Pr (>|z|) = .023). Moreover, there was a significant interaction between congruency and sentence type, showing that the increase in positivity for incongruent as compared to congruent trials was stronger when the sentential disambiguation pointed to a HA as compared to an LA structure (β = 1.394 t= 1.934, Pr (>|z|) = .053).

LAN (500-660 ms). In the left frontal ROI, there was a significant effect of congruency, showing higher mean amplitudes for incongruent as compared to congruent trials (β = 1.549, t= 2.758, Pr (>|z|) = .006). Also, there was again a marginally significant interaction between congruency and sentence type, where the abovementioned effect of congruency was stronger for HA as compared to LA disambiguation (β = 1.405, t= 1.771, Pr(>|z|) = .076).

Posterior P600 (580-640 ms). In the middle posterior ROI, there was a marginally significant effect of congruency, showing higher mean amplitudes for incongruent as compared to congruent trials (β = 0.975, t= 1.852, Pr (>|z|) = .063). There was again a significant interaction between congruency and sentence type, indicating that the effect of congruency was stronger for HA as compared to LA disambiguation (β = 1.771, t= 2.379, Pr (>|z|) = .024).

Frontal P600 (680-740 ms). In the middle frontal region, there was a significant effect of congruency, showing higher mean amplitudes for incongruent trials as compared to congruent trials (β = 2.434, t= 4.091, Pr(>|z|) < .001). Again, there also was a significant interaction between congruency and sentence type, showing that the increase in amplitudes for congruent versus incongruent trials was stronger for HA as compared to LA disambiguation (β = 2.175, t= 2.586, Pr (>|z|) = .010).

In summary, we found that several components we discussed earlier are affected by our manipulation of cross-domain structural congruency; these effects were often modulated by the sentential preferences of the participants. Averaged plots for each ROI with SE boundaries can be found in Figures 5,6,7 and 8.

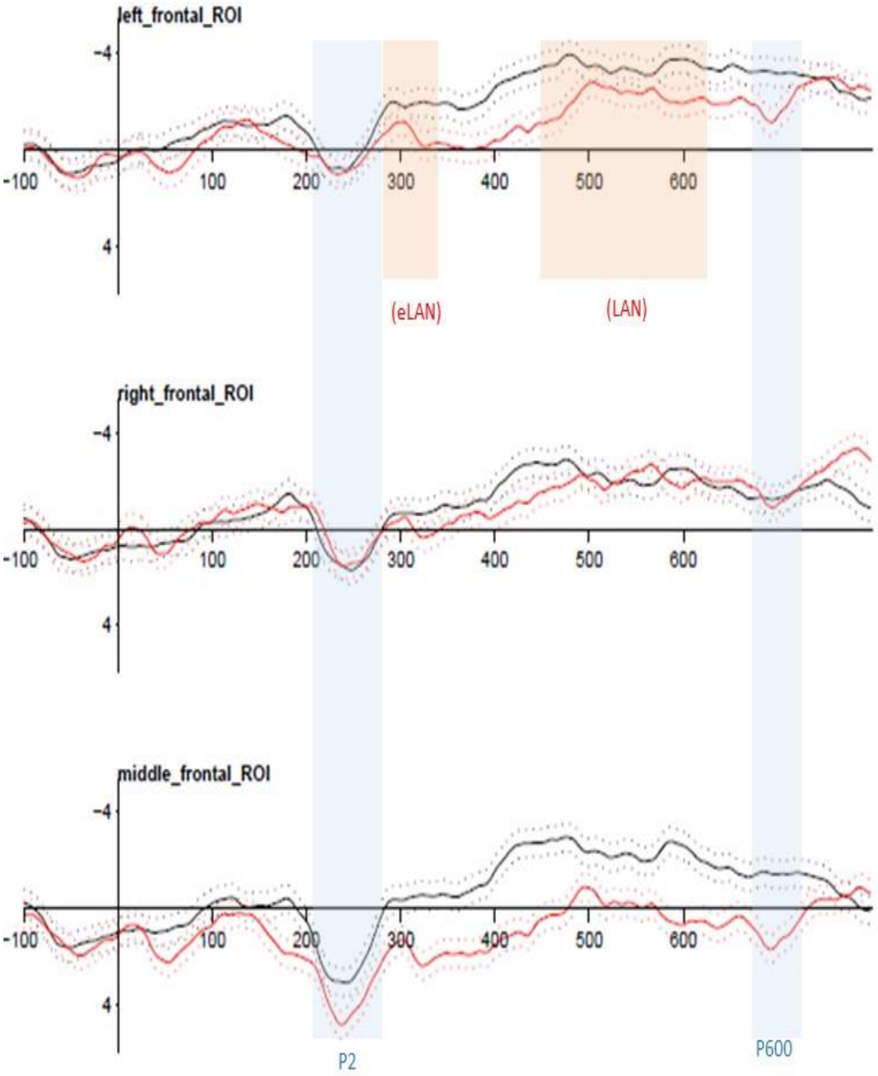

Figure 5: Overview of the wave forms for the three frontal ROI's when regarding HA sentences. The red line represents incongruent trials, whereas the black line represents congruent trials. Dotted lines represent standard error across participants. Y-axis reports mean amplitudes in microvolts, negative values are plotted upwards. X-axis reports time in ms from the presentation of the disambiguating verb.

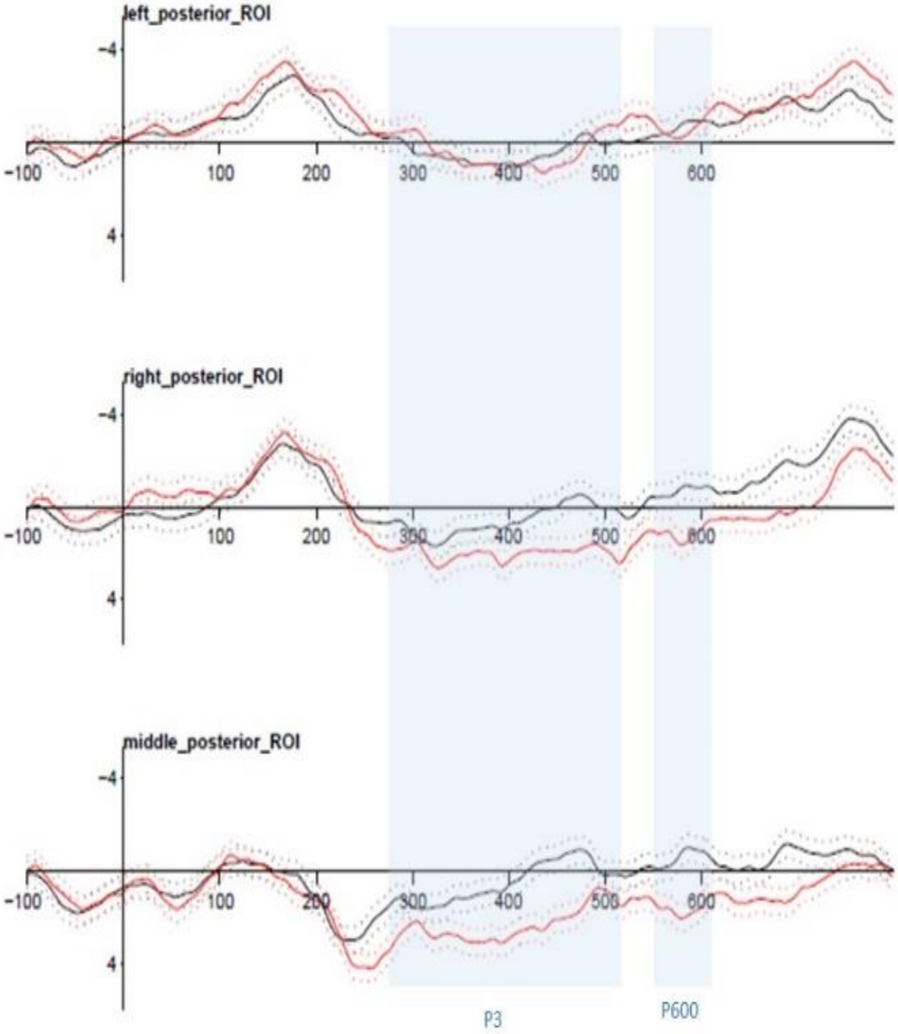

Figure 6: Overview of the wave forms for the three posterior ROI’s when regarding HA sentences. The red line represents incongruent trials, whereas the black line represents congruent trials. Dotted lines represent standard error across participants. Y-axis reports mean amplitudes in microvolts, negative values are plotted upwards. X-axis reports time in ms from the presentation of the disambiguating verb.

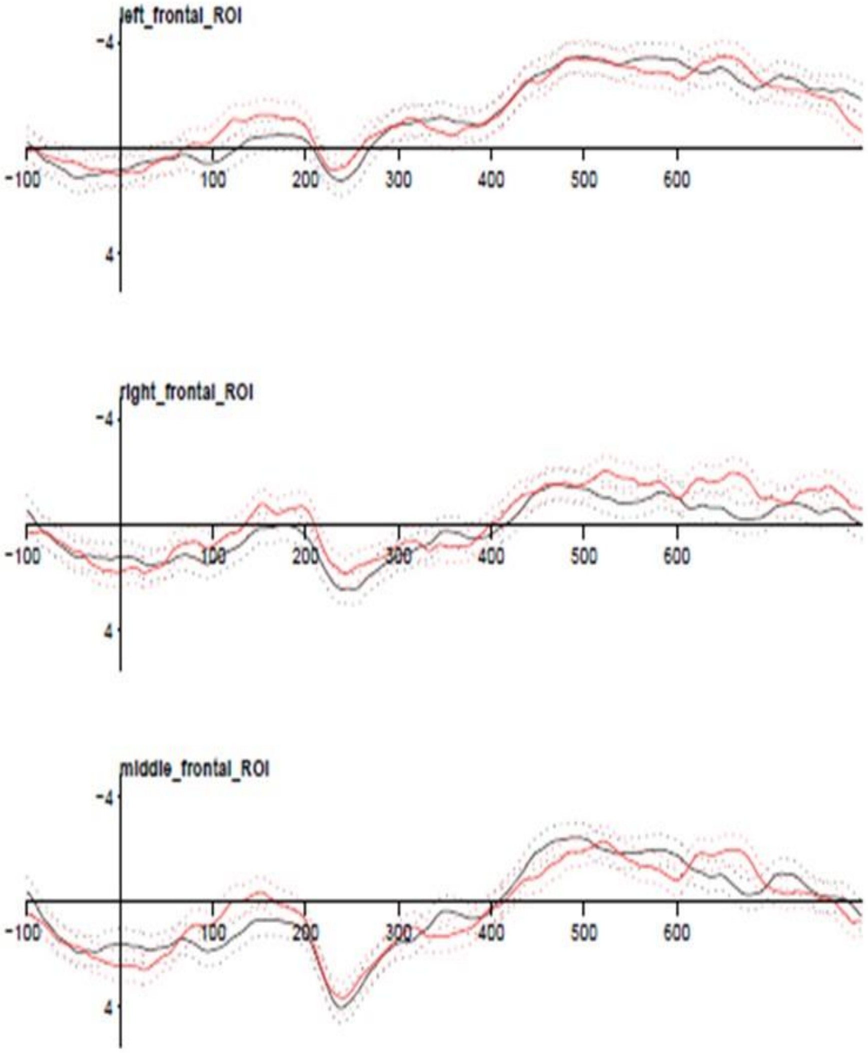

Figure 7 : Overview of the wave forms for the three frontal ROI's when regarding LA sentences. The red line represents incongruent trials, whereas the black line represents congruent trials. Dotted lines represent standard error across participants. Y-axis reports mean amplitudes in microvolts, negative values are plotted upwards. X-axis reports time in ms from the presentation of the disambiguating verb.

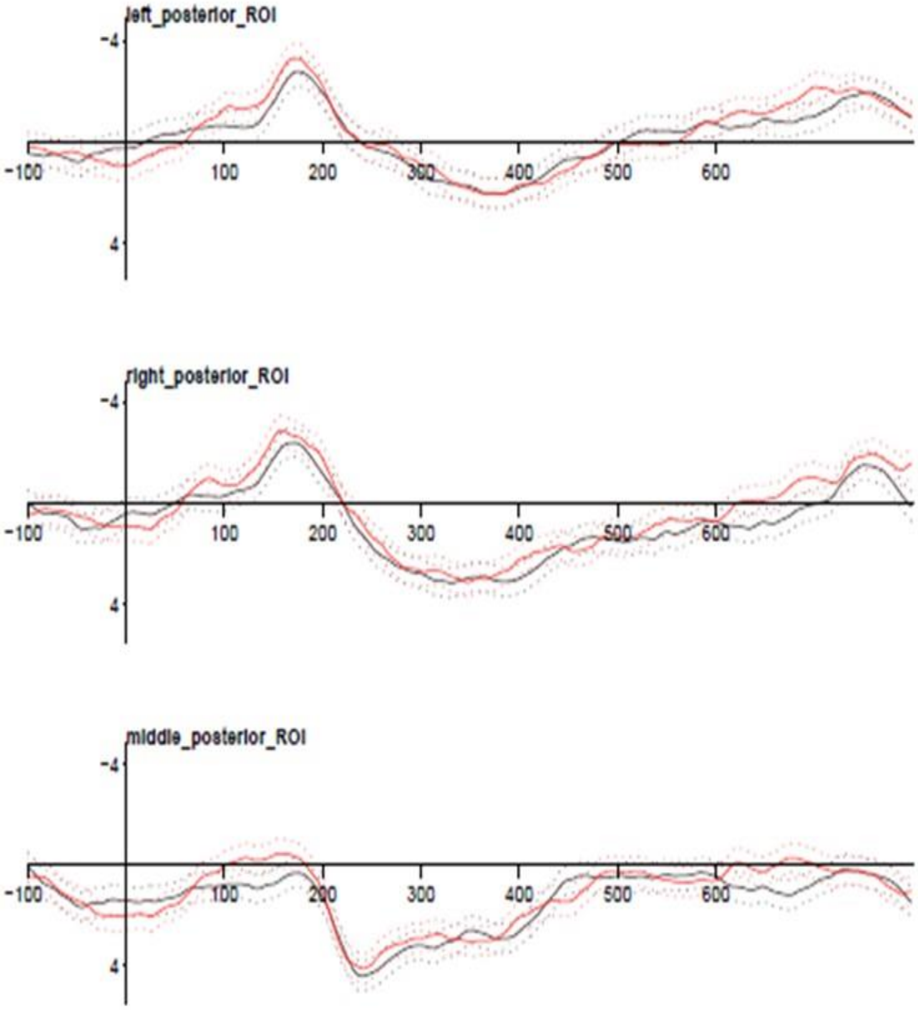

Figure 8 : Overview of the wave forms for the three posterior ROI’s when regarding LA sentences. The red line represents incongruent trials, whereas the black line represents congruent trials. Dotted lines represent standard error across participants. Y-axis reports mean amplitudes in microvolts, negative values are plotted upwards. X-axis reports time in ms from the presentation of the disambiguating verb.

DISCUSSION

In support of models suggesting a domain-general pool of resources for structural processing (Kljajevic, 2010), several studies have shown interference during the joint processing of structural difficulties across content domains (Koelsch et al., 2005; Slevc et al., 2009). Interesting as these findings might be, a recent debate has arisen about their interpretation, as any joint processing of unexpectancies (regardless of their structural nature) might evoke interference on the basis of for example attention or error monitoring (Perruchet & Poulin-Charronnat, 2013). Furthermore, it can be questioned how this simultaneous processing of structural difficulties relates to our everyday functioning Therefore, we asked to what extent the hypothesis of overlap in structural processing across domains can be investigated without such an experimental matching of unexpectancy manipulations.

In the current EEG study, we provided participants with a joint processing task in which they read sentences while listening to pitch sequences. Importantly, the sentences and pitch sequences did not contain any structural anomalies, and points of structural disambiguation were separated for both materials as well. However, we did provide a contingency between the attachment structure of the pitch sequence and that of the sentence. In 80% of trials, the attachment structure of the sentence would be congruent with that of the pitch sequence, and in 20% of trials the two would be incongruent. With a comprehension test for the sentences and a recognition task for the pitch sequences, we ensured attentive processing of both sets of materials.

The analysis of the behavioural measures showed that there were no differences in sentence comprehension or pitch recognition performance when comparing the incongruent as compared to the congruent trials. This suits with the idea that both conditions contain structurally sound materials, and that whatever processing difficulty might arise from the incongruency in integrational structures can be resolved into an accurate representation of both sentences and pitch sequences.

The EEG analysis showed event-related potentials in line with our a priori hypotheses. In the relevant time windows, there were main effects of congruency as well as interactions between congruency and the structure of the sentential disambiguation (typically with stronger effects for the less preferred structure). We found a P2a (200-280ms) , a P3 (300-500 ms) and a P600 (580-730 ms) across the frontal midline region, all of which were more pronounced on trials where the sentential disambiguation structurally mismatched the pitch sequence, especially if the sentential disambiguation resulted in a less-preferred attachment structure (for Dutch: HA). When regarding the wave plots of the electrodes in the left anterior ROI, the eLAN and the LAN can be observed for both congruent and incongruent trials. A visual inspection of the eLAN and LAN shows stronger negative-going amplitudes for incongruent as compared to congruent trials.

When interpreting these effects, we will turn to the midline positivities first. The P2 amplitude can be related to the visual processing of highly contextually constrained words (Federmeier & Kutas, 2002). It is unsurprising to find this component here, as the final verb of the sentence on which the EEG is time-locked, is highly contextually constrained (‘is’/’are’). The P3 amplitude can be related to attention allocation processes, which explains why the P3 amplitude is found to be higher for trials in which the sentential disambiguation is unexpected.

Our most important finding is that the incongruent trials of HA sentence disambiguations specifically evoke a P600. This component has been repeatedly linked to processes of structural reintegration and structural disambiguation. Therefore, more so than the increase in early components related to visual and attentional unexpectancy processing, this component clearly indicates that trials where the sentential disambiguation mismatched the basis of the pitch sequences induced structural reintegration, especially if the sentential disambiguation also mismatched linguistic preferences. The abovementioned results strongly suggest that event-related potentials measuring structural processing can be elicited through a manipulation of structural congruency across domains.

At this point, it is important to note that for the current experiment, we manipulated our trials to make participants expect structural congruency across domains. Therefore, finding unexpectancy effects in the incongruent trials might of course be related to a violation of this contingency rule, rather than a mismatching of attachment structure. One could argue that providing participants with 80% incongruent trials might have led to finding ‘structural unexpectancy’ effects for congruent trials. And indeed, eRAN components for example have been found on the basis of probabilistic manipulations (Pearce, Ruiz, Kapasi, Wiggins, and Bhattacharya, 2010). Similarly, the P600 has also been found to be sensitive to probabilistic manipulations within experiments (Coulson, King, & Kutas, 1998).

Regardless of whether the unexpectancy effects are based on structural similarity (i.e., congruent versus incongruent) or on task-related probabilities (i.e., frequent versus infrequent), there are several indications that the components we find are related to unexpectancies on the level of *structural processing*, rather than on the level of *final verb* prediction. A first is that our main finding concerns the P600 component. The occurrence of a P600 is related to unexpectancies on the level of morphosyntactic structure. The finding of a P600 thus suggests an effect beyond the prediction of the final word, towards the implications this final verb has for the integrational structure of the sentence. A second is that our effects interact with the structural preferences of the participants: unexpectancy effects are more pronounced when the ‘incongruent’ final verb points to a less preferred attachment structure (HA) as compared to when the ‘incongruent’ final verb points to a more frequently occurring attachment structure (LA).

In conclusion, not only do we find event-related potentials pointing to unexpectancy processing when sentential disambiguations mismatch the preceding pitch sequence structure, but furthermore, the nature of these potentials and their interaction with structural preferences in participants point to an unexpectancy at the level of structural processing. Thereby, the current findings have important implications for the recent debate (Slevc & Okada, 2015) concerning the sharedness of structural processing across domains, as well as the practical implications thereof.

CONCLUSION

The use of structural difficulties in materials is generally accepted to elicit structural integration components across domains. However, in several studies investigating the domain-generality of structural processing, the use of structural difficulties in materials has raised some concerns (Slevc & Okada, 2015). In the current EEG experiment, participants read sentences while listening to pitch sequences, which were structurally congruent in 80% of trials. We found that when the sentential disambiguation mismatched the earlier disambiguated structure of the pitch sequences in the incongruent trials, early and late processing components emerged, related to structural processing in language (P2, P3, and especially P600). The finding of such components on the basis of cross-domain structural contingencies rather than within-material manipulations might prove to be a worthwhile contribution in the ongoing debate on domain-general perspectives on structural processing (Slevc & Okada, 2015).

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APPENDIX

It might be worthwhile to investigate to what extent the ROI localisations based on previous research are supported by the data yielded in the current study. For the P2 (200-280 ms), we found that the middle frontal ROI displayed higher amplitudes as compared to the left frontal region ($\beta = 2.127$, $z = 3.149$, $Pr(>|z|) = .002$), the right frontal region ($\beta = 1.200$, $z = 1.750$, $Pr(>|z|) = .08$), the left posterior region ($\beta = 3.157$, $z = 4.674$, $Pr(>|z|) < .001$) and the right posterior region ($\beta = 2.127$, $z = 3.102$, $Pr(>|z|) = .002$), but not the middle posterior region ($\beta = 0.520$, $z = 0.759$, $Pr(>|z|) = .410$). It thus seems to largely be a midline positivity, as expected.

For the eLAN (280-340 ms), we found that the left frontal ROI displayed lower amplitudes as compared to the right frontal region ($\beta = 1.5638$, $z = 3.366$, Pr(>|z) < .001), the middle frontal region (β = 1.821, z = 3.921, Pr(>|z) < .001), the left posterior region (β = 2.172, z = 4.689, Pr(>|z) < .001), the right posterior region (β = 3.442, z = 7.409, Pr(>|z) < .001) and the middle posterior region (β = 4.6819, z = 10.07, Pr(>|z) <.001). The eLAN can thus be brought back to the left lateralized frontal ROI, as expected.

For the P3(300-500 ms), we find that the middle posterior ROI displayed higher amplitudes as compared to the left frontal region (β = 4.643, z = 10.760, Pr(>|z) < .001), the right frontal region (β = 3.422, z = 7.931, Pr(>|z) < .001), the middle frontal region (β = 3.493, z = 8.093, Pr(>|z) < .001), the left posterior region (β = 1.552, z = 3.598, Pr(>|z) < .001) and the right posterior region (β = 0.942, z = 2.183, Pr(>|z) = .029). The P3 can thus be located over the posterior midline section, as expected.

The LAN (500-640 ms) shows that there is a lower amplitude for the left frontal region as compared to the right frontal region (β = 1.778, z = 3.694, Pr(>|z) < .001), the middle frontal region (β = 1.341, z = 2.786, Pr(>|z) = .005), the left posterior region (β = 2.661, z = 5.540, Pr(>|z) < .001), the right posterior region (β = 3.566, z = 7.408, Pr(>|z) < .001) and the middle posterior region (β = 4.644, z = 9.650, Pr(>|z) < .001). In other words, the LAN can clearly be brought back to left lateralized frontal regions, as expected.

The posterior P600 (580-640 ms) shows that there are higher amplitudes over the middle posterior region as compared to the left frontal region (β = 4.497, z = 8.650, Pr(>|z) < .001), the right frontal region (β = 2.765, z = 5.316, Pr(>|z) < .001), the middle anterior region (β = 3.096, z = 5.953, Pr(>|z) < .001), the left posterior region (β = 1.996, z = 3.840, Pr(>|z) < .001), and the right posterior region (β = 1.165, z = 2.241, Pr(>|z) = .025). In other words, the posterior P600 can clearly be brought back to the midline posterior region.

The frontal P600 (680-740 ms) shows that there are higher amplitudes over the middle anterior region as compared to the left frontal region (β = 1.597, z = 2.630, Pr(>|z) = .009), but less high as compared to the ongoing amplitudes in the middle posterior region (β = 1.589, z = 2.613, Pr(>|z) = .008).

CHAPTER 4

EVIDENCE FOR STRUCTURAL PRIMING ACROSS MUSIC, MATH, ACTION DESCRIPTIONS, AND LANGUAGE [1]

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 (Slevc, Rosenberg, & Patel, 2009). These findings support theories of overlapping resources for integrational processing across domains (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 (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, 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, Scheepers et al., 2011, 2014), it remains to be investigated to what extent we can also find evidence for priming in other domains, such as music and action (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 colour 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.

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[1] Van de Cavey, J., & Hartsuiker, R.J. (2016). Is there a domain-general cognitive structuring system? Evidence from structural priming across music, math, action descriptions, and language. *Cognition*, 146, 172–184.

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, the functionality of these two domains seems to differ largely, and the meaningful elements as well as the syntactic rules governing them can be easily differentiated (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 (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 complex cognitive processes that analyse 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, behavioural (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 (Peretz & Coltheart, 2003), whereas the resource overlap would lead to interactions when both modalities are processed concurrently (e.g., Slevc et al., 2009). 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. This hypothesis has been represented in Figure 1.

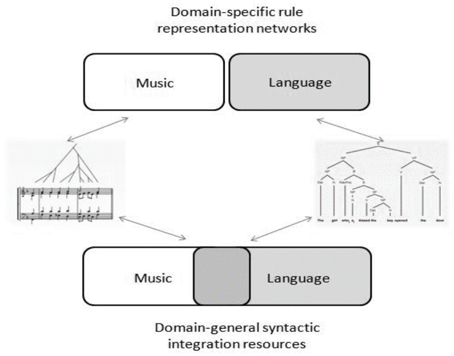

Figure 1: Representation of the SSIRH hypothesis (Patel, 1998). Whereas language and music both entail domain-specific formal knowledge networks, the structural integration of information processing in both domains is very similar. Therefore, it is suggested that whereas the rules on which this integration 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, further integrating new elements in the established structure. Importantly, this principle also entails that a long-distance dependency can be formed across 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 (similar to the SSIRH, Patel, 2003). The theory of syntactic working memory (Kljajevic, 2010) has extended its role beyond language to include music and arithmetic (Fiebach, Schlesewsky, Lohmann, von Cramon, & Friederici, 2005). The SWM (Kljajevic, 2010, Fiveash & Pammer, 2012) could be a domain-general interface acting upon domain-specific rule representations, an idea which strongly aligns with previous behavioural (e.g., Fedorenko et al. 2009) and neurological (e.g., Patel, Gibson, Ratner, Besson, & Holcomb, 1998) evidence in favour 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 musical unexpectancies, whereas no such 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 (e.g., *'give the child some candy'*) or a prepositional object dative (e.g., *'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, a study by 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 (e.g., *'lights'*) or late (e.g., *'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*'). It was found that the participant's choice for these relative clause completions could be primed by preceding relative clause attachments.

What distinguishes attachment priming from previous findings of structural priming, is that high versus low attachment sentences differ only 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, which 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, Van Laere, & Desmet, 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 structural complexity related to the height of attachment (low or high).

Most importantly for our purposes, attachment 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 (SSIRH, Patel, 2003). This argument is strongly supported by a recent study of Scheepers, Sturt, Myachykov, Teevan, and Viskupova (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 bidirectional influences between the processing of linguistic structure and mathematical equations. 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 incremental 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 which hypothesize domain-general systems (Fiveash & Pammer, 2012).

The aim of this study was 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). 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 the recent debate on domain-general cognitive resources (Slevc & Okada, 2015).

It is important to note that the auditory sequences we will present in these experiments are strictly speaking not musical sequences: the sequences were not harmonically composed, but generated by a computer program and they did not follow Western tonal harmony. We did this to be able to tap into music processing mechanisms on the basis of implicitly acquired experimental rules, rather than on the basis of music expertise that people might have acquired 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. Hence, 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 colour patches. Colour 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 (beyond language and music) would might also show interactions on the basis of domain-general aspects of structural processing(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.

EXPERIMENT 1A

Method

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.

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 (e.g., *'I saw the knives in the kitchen that were sharp'*) or a low-attachment (LA) structure (e.g., *'I saw the knives in the kitchen that 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 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', and 'Eb Ab Db', represented on the Circle of Fifths for Western musical keys in Figure 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 neighbouring keys on this Circle of Fifths, indicating a strong harmonic congruency between the tones within a cluster. Furthermore, the clusters are separated by one step on the Circle of Fifths for Western musical keys. It is plausible that participants tap into implicit knowledge about key distance relationships to aid the acquisition of the pitch clusters, yet 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.

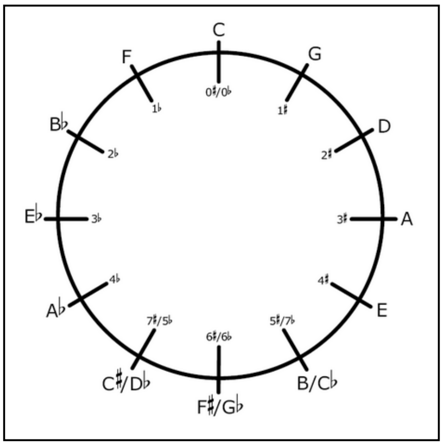

Figure 2: the clusters |A E B| , |F C G|, and |Eb Ab Db| consist of tones that are close to each other on the Circle of Fifths for Western musical keys. In comparison, switches between clusters would entail at least 2 or more steps on this Circle of Fifths. Given that the circle represents harmonic closeness 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 ‘neighbouring’ on average than pitch transitions between 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 was 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 low attachment 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 Figure 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.

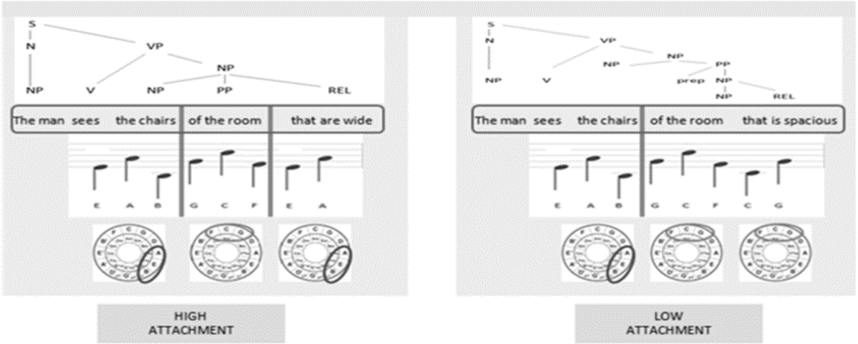

Figure 3: Overview of the materials. Whereas high attachment stimuli are characterized by an ‘ABA’-like structure with a long dependency, the low attachment stimuli are characterized by an ‘ABB’-like structure containing only no such long dependencies

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 (see Figure 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.

Figure 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.

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 cluster 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 structural boundary (*between*, 1/3 of trials). As in Tan et al. (1981) we expected a higher recognition performance for ‘within’ as compared to ‘between’ probes, indicating that the pitch sequence was indeed parsed along the pitch cluster boundaries as intended.

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.

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 pitch cluster manipulation, there was a recognition task after each pitch sequence. During the recognition task, the background colour 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 analysed. But 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.

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', and '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 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 3.2.3), using the lme4 package (version lme4_1.1-7). The data files and the R scripts can be found on http://opensciencework.org/profile/v49bp.

Results

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|) = .023). 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.

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|) = .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 (see Rowland et al, 2012, finding priming effects between 3-7 %). 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|) = .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).

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, 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 ('ABA' versus 'ABB') 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 colour sequences were used (e.g., red-blue-red for HA and red-blue-blue for LA).

EXPERIMENT 1B: COLOR SEQUENCE CONTROL

Method

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.

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’ ordered sequences. In the ‘LA’ sequences, the third color matched the hue (but not the shade) of the second color, but 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, but not the second color, resulting in an ‘ABA’ pattern. Each color square was 200x200 pixels in size on a 1280x1024 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 (non-identical) elements of the same category (e.g., ‘red’, EBG-cluster) and were also analogous in the overall time course of presentation.

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. 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).

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 color 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 Experiment 1a and 1b.

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, 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 (Pr (>|z|) = .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 could be tested whether there was a significant priming difference between the two experiments. All analyses were ran on R (version 3.2.3), using the lme4 package (version lme4_1.1-7). The data files and the R scripts can be found on http://opensciencеframework.org/profile/v49bp.

Results

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.

Sentence completion task. No significant effects of prime structure on relative clause completion was found (where ‘ABA’-structured color primes yielded 59% LA completions, ‘ABB’ structured color primes yielded 57 % LA completions). However, we did find a marginally significant (β = 0.185, z = 1.676, Pr (>|z|) = .097) tendency for priming from relative clause completions on the previous trial.

Contrasting Experiment 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 ($\beta = 0.332$, $z = 2.164$, $Pr(>|z|) = .030$) larger than in Experiment 1b.

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. For an extension of this control experiment, see Appendix 1 at the end of this dissertation.

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.

EXPERIMENT 2

Experiment 2 presented prime sequences in four modalities: structured pitch sequences (Experiment 1a), sentences containing a relative clause structure (Scheepers, 2003), arithmetic equations (Scheepers et al., 2011), and sentences referring to goal-directed actions (thus including a non-syntactic attachment structure). When describing goal directed behaviour, the sentence can be processed according to the ‘means-end’ structure of the described actions (Allen, Ibara, Seymour, Cordova & Botvinick, 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 *‘cut the paper’*), 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 previous segment *‘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 means-end sentences used in this study 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 support priming and facilitation effects (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.

Method

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.

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, but 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 a relative clause attachment prime condition, in which the high attachment (HA) and low attachment (LA) structures were created by providing unambiguous sentence beginnings (e.g.: *'de kunstenaar maakte het logo van de artiesten die… '*, translated as '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 (Scheepers, 2003), resulting in LA or HA attachments. Hence, 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 Scheepers et al. (2011). 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. For an overview of all the priming materials, see Appendix 3 at the end of the dissertation.

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 structured sentences.

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.

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, participants vocally repeated and 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 repeated and 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 for the visually presented prime equations.

After each prime task, an incomplete, 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, but 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'*.

Analysis. After data collection, the sound recordings (containing the full sentence productions of the participants) were individually rated. Similar to Experiments 1a and 1b, 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 available when rating the sentence completion on the recordings, which thus provided 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, (e.g., *'I open the closet, grab the keys, and sit back down again'*), or if (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' or '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 to 5) , and ‘Music interest’ (time spent listening to different music, score 1 to 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’, or ‘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.

Furthermore, 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. 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 the abovementioned analyses were ran on R (version 3.2.3), using the lme4 package (version lme4_1.1-7). Also for these analyses, the data files and the corresponding R scripts can be found on http://openscienceframework.org/profile/v49bp

Results

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 (β = 0.369, z = 1.842, Pr (>|z|) = .065) effect. 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. Also, we found the advantage in recognition performance for 'within probe' as compared to 'between probe' performance to be better for LA primes (β = 0.878, z = 3.961, Pr (>|z|) < .001). Upon analyzing the covariates of the musicality questionnaire, we found that the general performance was not attenuated by musical expertise (β = -0.028, z = -1.197, Pr (>|z|) = .231) or exposure (β = 0.195, z = 1.887, Pr (>|z|) = .060) , and also the boundary effect was not attenuated by musical expertise (β = 0.090, z = 1.058, Pr (>|z|) = .124) or exposure (β = 0.067, z = 0.284, Pr (>|z|) = .770). 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 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.

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.

Priming Analyses. An overall analysis on the type of target responses by priming domain, priming structure, and target condition, showed that there were significantly ($\beta = -0.367$, $z = -3.676$, $Pr (>|z|) < .001$) 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) = .870), nor the domain in which this previous target was construed (Pr (>Chisq) = .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 ($\beta = 0.593$, $z = 3.567$, Pr (>|z|) < .001). 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 ($\beta = 0.438$, $z = 2.727$, Pr (>|z|) = .006), revealing 10% more LA completions after a LA prime. There were no significant interactions between structural priming and the domain of priming (Pr (>Chisq) = .559), and neither was there an effect of musical expertise (Pr (>Chisq) = .919). The percentage of LA responses in LA and HA prime conditions respectively was 71% and 60% for attachment priming, 68% and 59% for math priming, 71% and 60% for means-end priming, and finally 66% and 57% 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 Figure 5).

In the analysis of the *means-end* targets, there is a significant priming effect ($\beta = 0.746$, $z = 4.386$, Pr (>|z|) < .001) 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 55% and 45% for attachment priming, 53% and 45% for math priming, 59% and 40% for means-end priming, and 52% and 49% 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|) = .060). Similarly, math primes showed an 8% low attachment priming effect, which entails a significant change ($\beta = -0.421$, $z = -2.160$, Pr (>|z|) = .031). Finally, the musical primes show only a small 4% attachment priming trend, thereby clearly ($\beta= -0.600$, $z = -3.130$, Pr (>|z|) = .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 (Figure 6).

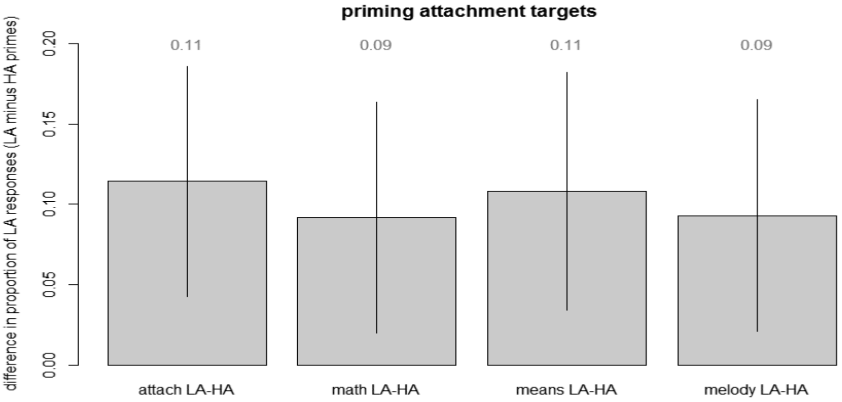

Figure 5: Priming Analysis Attachment targets Experiment 2. The displayed results are the following difference scores: percentage of LA responses after LA primes minus the percentage of LA responses after HA primes. The priming effects are jointly presented with their respective confidence intervals.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

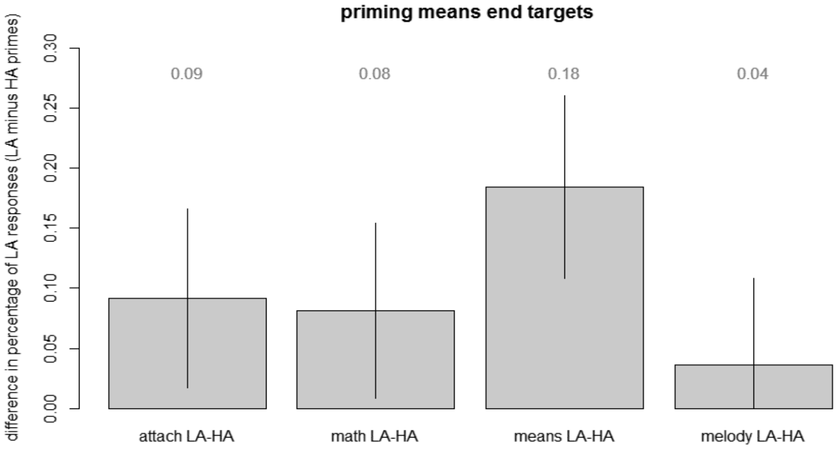

Figure 6: Priming Analysis Means-end targets Experiment 2. The displayed results are the following difference scores: amount of LA responses after LA primes minus the amount of LA responses after HA primes. The priming effects are jointly presented with their respective confidence intervals. The confidence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

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|) < .002), math primes ($\beta = 0.413$, $z = 2.24$, Pr (>|z|) = .025), means-end primes ($\beta = 0.452$, $z = 1.858$, Pr (>|z|) = .06), and melodic primes ($\beta = 0.386$, $z = 2.279$, Pr (>|z|) = .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|) = .280). The other conditions did show significant priming effects: attachment primes ($\beta = 0.3647$, $z = 2.105$, Pr (>|z|) = .035), math primes ($\beta = 0.316$, $z = 2.187$, Pr (>|z|) = .029), and a large effect for means-end primes ($\beta = 0.826$, $z = 5.483$, Pr (>|z|) < .001).

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 (Scheepers et al., 2011) and action description (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.

GENERAL DISCUSSION

Behavioural 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. However, the use of within-material unexpectancy manipulations (e.g., Slevc et el., 2009) to provide evidence for such an overlap in structure processing resources has been under debate lately (e.g., Slevc & Okada, 2015). The reported experiments therefore aspired to provide evidence in favor of shared structural processing, by showing sequential influences from attachment choices in one domain to another domain.

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 can we find similar priming effects with means-end stimuli created in a visual or spatial domain?’. This is a topic that has been further elaborated upon in the discussion chapter of this dissertation.

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 (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

(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 (2011) 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 (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, 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 study 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.

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 (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, 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, 2011, 2013) 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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CHAPTER 5

PRIMING BEYOND LANGUAGE: CONTINUATION OF STRUCTURAL PREFERENCES IN THE PROCESSING OF NON-LINGUISTIC AUDITORY SEQUENCES[1]

Whereas such structural processing is often accounted for in domain-specific theories, several neurophysiological and behavioural studies suggest a more domain-general perspective. A recent contribution to the evidence pleading for a domain-general framework stems from priming studies (e.g., Van de Cavey & Hartsuiker, 2016), which show persistence in structural processing across different domains. A limitation to the findings of cross-domain priming studies, however, is that effects have thus far only been found for measures that require explicit, verbal processing of written information (e.g., producing sentences or solving arithmetic equations). If such cross-domain priming is indeed an indication for an overlap in the mechanisms underlying our structural processing, we should also be able to find such priming on more implicit measures. In this study, we tested whether the processing of prime sequences in several domains (adapted from Van de Cavey & Hartsuiker, 2016) could influence the subsequent processing of implicitly structured pitch sequences. We provided participants with simple pitch sequences, after which they performed a recognition task. In this recognition task, we measured to which extent the implicit boundary structure of the pitch sequence was processed. Importantly, this implicit boundary structure could be congruent or incongruent with the structure of a preceding prime sequence. We found that if prime and target structures were different, there was a heightened processing of the incongruous boundaries in the pitch sequence structure. Moreover, this pattern of findings was found across linguistic (relative clause structures, means-end structures) and non-linguistic (pitch sequence structures) priming materials. Our results thus strongly suggest that structural priming effects within and across domains can be found on the processing of implicit boundary structures during auditory comprehension. This indicates that such cross-domain structural priming effects seem to be based on an overlap in the implicit mechanisms underlying structural processing.

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[1] Van de Cavey, J. & Hartsuiker, R. J. (Submitted). Priming beyond Language: continuation of structural preferences in the processing of non-linguistic auditory sequences.

INTRODUCTION

The construction of a hierarchically organized structure is an important aspect of language processing (Bock, 1986; Frazier & Rayner, 1982). Though most theories of language processing assume this syntactic processing to be a language-specific process (e.g., Pickering, Branigan, Cleland, & Stewart, 2000), the construction of a hierarchically organized structure is also necessary for processing in other cognitive domains, such as music or mathematics. And in contrast to the modular conceptualization of such structural processing across content domains (Dependency Locality Theory, DLT, Gibson, 2000; Generative Theory of Tonal Music, GTTM, Lerdahl & Jackendoff, 1983), it is striking that many of the described processing mechanisms are similar across domains (Barret & Kurzban, 2006). For instance, the process of dealing with dependency relations is central in both theories of structural processing in music and language.

Such similarities have sparked recent hypotheses (Shared Syntactic Integration Resource Hypothesis, SSIRH, Patel, 2008; Syntactic Working Memory, SWM, Kljajevic, 2010) which suggest that, regardless of domain-specific structuring rules, the (working memory) resources and mechanisms required for the integrational processing of dependencies might overlap across domains.

In the past decade, several studies provided evidence for such an overlap by evoking interference during the simultaneous structural processing of linguistic and non-linguistic materials (i.e., in dual-task paradigms). However, this literature almost exclusively focuses on studying the effects of structural unexpectancies in a non-linguistic domain on linguistic structure processing. Linguistic structural processing would then be measured as changes in electrophysiological potentials (Koelsch, Gunter, Wittfoth & Sammler, 2005; Maess, Koelsch, Gunter, & Friederici, 2001; Sammler et al., 2009) and behavioural effects (e.g., the reading time measurement of ‘garden path’ effects, like Slevc, Rosenberg, & Patel, 2009). To evoke such behavioural and electrophysiological effects, linguistic materials often contain structural unexpectancies (e.g., ‘garden path’ errors). Thus, demonstrations of shared structural processing often relied on the simultaneous presentation of structural unexpectancies. Concerns about these aspects of the task have led to alternative accounts, such as suggestions that the interference is caused by more general attentional and error-monitoring resources (e.g., Perruchet & Poulin-Charronnat, 2013).

An interesting alternative to the abovementioned interference studies are the recent findings of structural priming across domains. Structural priming is generally referred to as the phenomenon where the structural processing of preceding material enhances the chances of a similar structure being applied in the processing of subsequent material (Bock, 1986; Pickering & Ferreira, 2008). Structural priming has been replicated across languages (Loebell & Bock, 2003; Ferreira & Bock, 2006) and structures (Loncke, Van Laere, & Desmet, 2011; Rowland, Chang, Ambridge, Pine, & Lieven, 2012). Important to the current research topic, structural priming has recently also been reported across sentences and non-linguistic written structure (e.g., mathematical equations). Scheepers, Sturt, Martin, Myachykov, Teevan, and Viskopuva (2011) have found persistence in the structural processing from written arithmetic equations to the attachment structure of relative clause sentences. More specifically, they provided participants with mathematical equations that differed in their structural dependencies (e.g., *‘80+9+1*5’*, which consists only out of short dependencies, versus *’80+(9+1)*5’*, which contains a long dependency). They found that after solving a math equation with a long dependency, participants were more likely to complete a relative clause sentence (e.g., *‘The tourist guide mentioned the bells of the church that…’)* with a similar long dependency (i.e., making a completion in which the relative clause attaches to ‘*the bells’* instead of *‘the church’).* A similar cross-domain priming finding has been found from linguistic structure to the completion of arithmetic equations (Scheepers & Sturt, 2014).

Recently, Van de Cavey and Hartsuiker (2016) found cross-domain priming effects for both linguistic and non-linguistic integrational structures in the visual and auditory domains. They found priming effects in four priming domains. One domain was mathematical equations, in which the findings of Scheepers et al. (2011) were replicated. Second, there was a relative clause prime condition, in which high attachment and low attachment structures were created by providing unambiguous sentences (e.g.: *'I saw the knifes of the cook WHO was fired'*) that needed to be read and remembered (Scheepers, 2003). Third, there was an action goal prime condition, in which the high attachment and low attachment structures were created through enabling/end actions (Allen, Ibara, Seymour, Cordova, & Botvinick, 2010). For example, *'I take my phone, cover the wound, and call the police'* would be a high attachment structured means-end sequence, since it contains a long dependency between the enabling action (*'take the phone')* and its respective means-end action (*'call the police').* On the other hand, a sentence like *'I cover the wound, take my phone, and call the police'* would be a low attachment structured sequence, since it contains a short dependency between the enabling and respective end action. In this priming condition (similar to the attachment prime condition), participants had to read and remember non-ambiguous means-end sentences (e.g.: *'I take the toothbrush, open the window, and brush my teeth'*). Note that the action goal sentences were always unambiguous, given that one of the two actions was a non-preparatory action. Fourth, there was also an auditory sequence condition, in which pitch sequences were provided with a high or low attachment structure regarding pitch boundaries. These pitch sequences were created in an identical manner to the target pitch sequences used in the experiment reported below.

The findings of Van de Cavey and Hartsuiker (2016), and specifically the novel findings of structural priming from auditory sequences to written sentence completion and priming effects on means-end sentence completion, strongly support the idea of overlap in the structural processing of linguistic and non-linguistic materials. In contrast to the interference studies mentioned earlier (Slevc et al., 2009), such priming effects are not based on simultaneous processing of structural difficulties. Where the finding of interference in simultaneous processing has been strongly debated over the past few years (Slevc & Okada, 2015), structural priming offer a new perspective on the idea of domain-generality in structural processing.

Regardless of their contribution, one important limitation of previous cross-domain priming studies is that the priming effects have always been measured on the explicit structural processing of written materials (i.e., the completion of sentences, or the resolution of mathematical equations). Therefore, as compared to the more implicit nature of interference findings in the double-task paradigms, structural priming findings might be more susceptible to conscious choices or strategies. Based on the idea of an overlap in implicit structuring mechanisms, one might expect that similar cross-domain priming effects should also be found when measuring the implicit structural integration of materials, rather than conscious processing.

In the current study, we therefore wanted to investigate whether cross-domain structural priming (Scheepers et al., 2011; Scheepers & Sturt, 2014; Van de Cavey & Hartsuiker, 2016) can also be observed when, instead of a conscious completion of written materials, we measured the implicit structural processing of auditorily provided pitch sequences. We therefore created linguistic and auditory prime sequences through the same procedure as Van de Cavey and Hartsuiker (2016), and presented three kinds of priming materials: pitch sequences, sentences with a relative clause, and sentences with a means-end action structure. Prime and target sequences either had a high attachment or low attachment structure. We then tested whether these priming materials influenced the processing of a subsequent auditory target sequence. In the remainder of the introduction, we first explain our measure of integrational structure processing in auditory sequences. Next, we explain the structure of our pitch sequences, and we then sketch detailed predictions for our experiment.

The Boundary Processing Effect (BPE)

Our measurement of the structural integration of experimentally manipulated pitch sequences was based on an early study by Tan, Aiello, and Bever (1981). These authors claimed that with repeated exposure to a culture’s music, listeners implicitly acquire expectations concerning what pitches follow others, based on the harmonic relationship between pitches. These expectations allow us to detect key shifts, thereby phrasing the sequence. Tan et al. found evidence for this hypothesis by providing participants with a simple melody, containing a harmonic boundary. They found that it was more difficult for the participants to recognize a subsequently presented two-tone probe as sequentially occurring in the melody when the tones spanned a harmonic boundary in the melody, than when the tones were within a harmonic segment (see Figure 1).

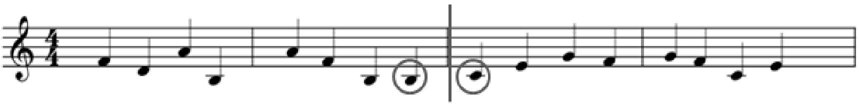

Figure 1: schematic overview of the 'probe recognition task' by Tan et al. (1981). The line indicates that the melody changes its tonic halfway through the melody. This causes participants to have more difficulties in recognizing the two encircled tones as occurring in sequence ('between phrase' probes) as compared to two tones that do not span a harmonic boundary ('within phrase' probes).

Importantly, Tan et al. (1981) argued that this advantage in recognition performance for tones within the same harmonic phrase (so-called 'within' probes) as compared to tones spanning a harmonic boundary (so-called 'between' probes) is an effect of structurally processing the melody. This 'within probe' advantage would occur because implicitly phrasing the melody according to its harmonic structure would increase the recognition accuracy for 'within probes' and decrease the recognition accuracy for 'between probes'.

Following this reasoning, we expected that this 'within probe' advantage (i.e., higher performance for 'within phrase' probes versus 'between phrase' probes) would occur more strongly for pitch sequences in which the harmonic structure was processed better. After all, a stronger processing of the harmonic boundary should entail that the representation of the melody is more strongly parsed along this boundary.

We can draw this line of reasoning further into a measure of implicit structure processing of the melody. When comparing the recognition performance for a melody containing a well processed harmonic boundary as compared to an ill-processed harmonic boundary, we should find a higher 'within probe' advantage in the former case. This interaction between the 'within probe' advantage on recognition performance and the amount to which the boundary is represented, is denoted as the Boundary Processing Effect (BPE). The next section explains the development of the target auditory sequences on which this recognition probe measure was used.

Dependency structures in pitch sequences

As mentioned earlier, we adapted three sets of priming stimuli from Van de Cavey and Hartsuiker (2016), in which materials were created to have either a high or a low attachment structure. To measure possible influences of priming on the implicit processing of our auditory target sequences, a similar distinction between high and low attachment structures was made in these target pitch sequences. We created 6-pitch sequences by selecting pitches out of three possible clusters: 'A E B','F C G', and 'Eb Ab Db'. The presented pitches ranged from 196.00 to 698.46 Hz. In all sequences, pitches were always followed by pitches from the same cluster, except on certain positions. Between the 2nd and the 3rd, and later between the 4th and the 5th pitch, a cluster shift could occur.

To create high attachment target sequences, we made sure that there was a structural boundary (i.e., a cluster shift) in both the first and the second region, whereby the cluster transition in the second region meant a shift back to the initial cluster of the pitch sequence. Through this manipulation, we created a long structural dependency in the pitch sequence through the use of two cluster transitions. To create low attachment structures, we provided a structural boundary in the first, but not the second critical region, so that there was only one long segment and no long dependency in the pitch sequence structure. Importantly however, we did provide a superficial boundary (i.e., frequency shift within the same cluster) in our low attachment structured pitch sequences. More information can be found in the methods section.

Expected effects of structural processing and priming on the probe recognition task

When applying the probe recognition task of Tan et al. (1981) to the target sequences, we expect to find a Boundary Processing Effect (BPE, expressed as a stronger 'within probe' advantage) when investigating a region containing a structural boundary as opposed to a superficial boundary. After all, only a structural boundary entails a cluster shift, thereby structurally segmenting the pitch sequence. This can be seen as a confirmation that the target sequence is indeed implicitly structured according to the cluster shift dependencies, rather than superficial frequency changes. Specifically, we would expect a higher 'within probe' advantage when comparing on the one hand structural boundaries (present in the first and second regions in high attachment targets and the first region in low attachment targets), and on the other hand superficial boundaries (present in the second region in low attachment targets).

This leaves us to hypothesize on the possible effect of preceding prime structures on the processing pattern described above. Based on previous structural priming studies (Van de Cavey & Hartsuiker, 2016), we state that the processing of prime structures governs structural expectancies during the processing of our subsequent materials, both within and across domains. As a result of this expectancy formation, we assume that structural elements which are incongruent with the prime structure might be unexpected. As modelled in several constraint-based and resource-based models for structural processing (Levy, 2008), the occurrence of integrational structures which are unexpected or dispreferred is said to invoke more attention and higher resource demands. In our recognition task, we might thus find a more thorough processing of such unexpected elements in the target structures. In our target pitch sequences, the first critical region always contains a structural boundary, which is thus always congruent with both LA and HA prime structures. However, the second critical region discerns between HA and LA targets (by containing respectively a structural or superficial boundary), and thus includes unexpected structural elements for targets mismatching the prime structure. Therefore, we might expect a more thorough processing of the second region when the target structure is incongruent with that of the prime.

It is important to note however that the behavioural effects of a more thorough processing in the second critical region are quite different for HA and LA targets. Overall, we expect a more thorough processing of the second critical region to lead to a stronger BPE: the difference in ‘within probe’ advantage between superficial and structural boundaries will increase. In HA targets, more thorough processing in the second critical region will lead to a more accurate processing of a structural boundary, and thus to the representation of the target sequence being more strongly parsed along this boundary (i.e., higher ‘within probe’ advantage) as compared to when the prime structure is congruent with the target structure. In LA targets, more thorough processing in the second critical region will lead to a more accurate processing of a superficial boundary, and thus to the representation of the target sequence being less parsed along this boundary (i.e., lower ‘within probe’ advantage) as compared to when the prime structure is congruent with the target structure.

Furthermore, we note that a more thorough processing of the second region of course also entails a resource allocation to this second critical region. Therefore, though the first critical region is not structure-specific and thus always expected regardless of prime-target structure congruency, we might expect a slightly less thorough processing for this first critical region when the target structure is incongruent with the prime structure. After all, we expect a resource shift to the second critical region. Behaviourally, this would entail that the structural boundaries presented in the first critical region are processed less well when prime structure is incongruent as opposed to congruent with target structure, leading to a decreased ‘within probe’ advantage. In short, the expected effects concerning structural processing and priming on our recognition task can be summarized as represented in Figure 2.

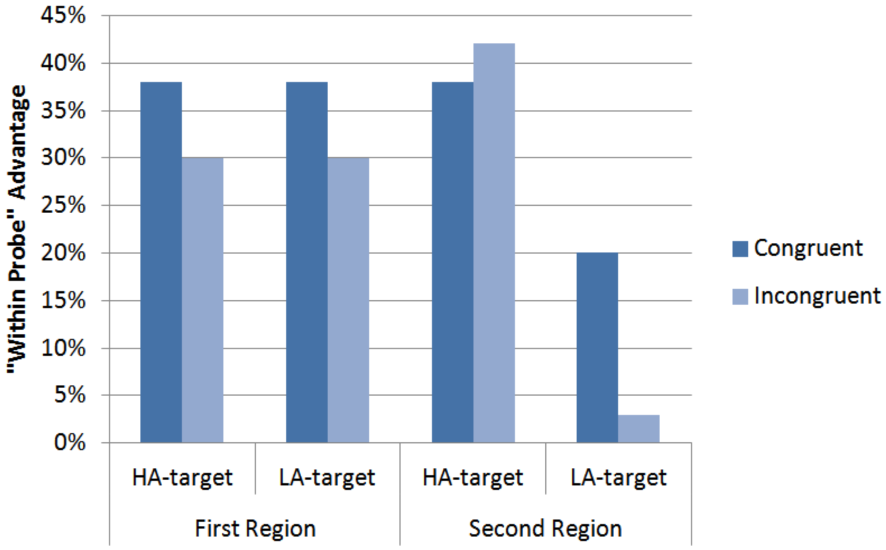

Figure 2: Overview of the expected interaction between prime structure congruency and the BPE.

Regarding the structural processing of our target pitch sequences, we would expect all structural boundaries (first region and second region in the case of high attachment structured targets) to show a higher 'within probe' advantage as compared to the superficial boundaries (second region in the case of low attachment structured targets). This is what we have summarized under the Boundary Processing Effect (BPE). Regarding priming effects, we expect that when the prime structure is incongruent with the target structure, the unexpected elements in the second critical region will be processed more thoroughly. This will lead to a higher BPE in the second critical region after incongruent versus congruent prime structures, as the 'within probe' advantage for the structural boundaries in HA targets increases, and the 'within probe' advantage for the superficial boundaries in LA targets decreases. Additionally, more thorough processing in the second critical region might entail a less thorough processing of the structural boundaries in the first critical region. Therefore, we might expect a decreased 'within probe' advantage in the first critical region after incongruent versus congruent prime structures.

METHOD

Participants

We recruited 30 participants from the student pool of Ghent University (average age = 18), who participated for course credits (29 female, one male). This number was decided upon a-priori, and we ran the experiment until the predetermined sample size of 30 participants was reached. Though participant selection was unrelated to the participants' musical expertise, we measured the amount of musical training (which ranged from 0 to 12 years, mean is 1 year), a factor that was later included as an independent variable.

Materials

Target Sequences. There were 216 target sequences, each consisting of 6 pitches. We created artificial pitch sequences as target stimuli (and in one condition as prime stimuli), to ascertain that familiarity with existing music could not be applied to the pitch sequences to process their underlying structure. The pitches were sine waves and had a fixed duration of 230 ms. Their frequencies ranged from 196.00 to 698.46 Hz and corresponded to 18 pitches: G, Ab, A, B, (middle) C, Db, Eb, E, F, and repeated one octave higher. Pitches were separated by 70 ms silences.

The first tone of every pitch sequence was randomly selected out of the 18 tones. From this first tone, the 'pitch cluster' was determined. There were three pitch clusters (notes A-B-E, notes Ab-Eb-Db, and notes C-F-G). Each following tone was created to be the closest neighbour of the preceding tone, within the same ‘pitch cluster’. When the pitch sequence was manipulated to have *a structural boundary*, the following tone would be randomly selected from a different ‘pitch cluster’, thus instigating a segmenting of the pitch sequence along this boundary. When the pitch sequence was manipulated to have a *superficial* boundary, the following tone would be randomly selected, but still within the pitch cluster of the preceding tone (neighbours excluded). These superficial boundaries acted as a control for our structural boundaries. Importantly, whereas the structural boundaries induced a shift in both frequency (not the closest neighbour) and pitch cluster, the superficial boundaries only induced a strong shift in frequency. Therefore, if the participants truly structured the pitch sequence according to our cluster manipulation and not on the basis of the accompanied frequency shifts, we should find a BPE when contrasting structural boundaries to superficial boundaries.

There were two critical regions in the pitch sequence where a structural or superficial boundary could occur. The first critical region was the transition between the second and third tone, during which a *structural boundary* (i.e., third tone was randomly selected from a pitch cluster different to the second tone) was always present. The second critical region was the transition between the fourth and fifth tone, during which either a *structural boundary (*i.e., fifth tone was randomly selected from a pitch cluster different to the fourth tone) or a *superficial boundary* (i.e., fifth tone was randomly selected from the same pitch cluster as the fourth tone, but neighbours were excluded) could occur. Importantly, if there was a structural boundary in this second critical region, the new pitch cluster that was selected was the initial pitch cluster.

We can therefore distinguish two types of pitch sequence. On the one hand, after the initial structural boundary in the first critical region, there can also be a structural boundary in the second critical region, thus inducing a recurrence of the initial cluster. This is very similar to the dependency structure of a ‘high attachment’ sentence found in the relative clause attachment priming paradigms (e.g., *‘I saw the lights of the room that were bright’*). On the other hand, the structural boundary in the first critical region can also be followed by a superficial boundary without an underlying cluster shift. This is very similar to the dependency structure of a ‘low attachment’ sentence found in the relative clause attachment priming paradigms (e.g., *‘I saw the lights of the room that was big’*). A graphic representation can be found in Figure 3.

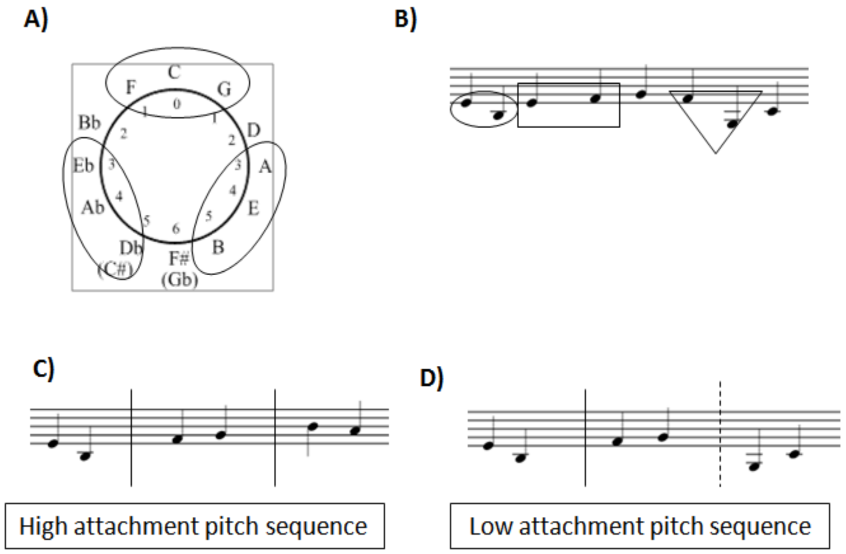

Figure 3: **A)** an overview of the three selected pitch clusters. **B)** In the oval, an example of a normal transition is provided. Following the preceding tone (E4), a neighbour within the cluster is selected (B3). In the rectangle, an example of a structural boundary is provided. Following the preceding tone (E4), a tone is randomly selected from a different cluster (F4). In the triangle, an example of a superficial boundary is provided. Following the preceding tone (F4), a tone is randomly selected from the same cluster, neighbours excluded (G3). Note that because of this manipulation, frequency shifts are usually higher for superficial boundaries as compared to structural boundaries. **C)** Example of a ‘high attachment’-like pitch sequence. There is a structural boundary on the first and the second critical region. The structural shift on the second critical region leads back to the initial cluster. **D)** Example of a ‘low attachment’-like pitch sequence. There is a structural boundary on the first critical region. There is a superficial boundary on the second critical region.

Pitch Recognition Probes. Following each of the 216 target pitch sequences, participants performed a recognition task, in which they had to accurately judge whether a two-tone probe was present in the pitch sequence. 1/3 of these probes were *foils,* meaning that the probe consisted out of 2 randomly selected tones that were not sequentially presented in the melody (though both were individually present in the target sequence). Of the other probes, 1/3 were 'within segment' probes, randomly selected to be the first and second, the third and fourth, or the fifth and sixth tone. The other probes were 'between segment' probes. Half of these were selected from the two tones spanning the first critical region, the other half were selected from the two tones spanning the second critical region.

Priming Sequences. Priming sequences were created in three different domains, similar to Van de Cavey and Hartsuiker (2016). For the musical domain (72 trials per participant), pitch sequences were constructed in the exact same fashion as the target pitch sequences (random selection of first pitch, followed by a randomized selection of within and between cluster pitches. Half of the sequences followed a HA structure, and the other half followed a LA structure. Pitch sequences were randomly generated with the same pitch sequence generator program as used by Van de Cavey and Hartsuiker (2016).

A second type of priming sequence consisted of sentences ending with a relative clause (Scheepers, 2003) that could either be attached to the first or the second of two nouns (72 trials per participant). The sentences were in Dutch (e.g., *'Ik zag de konijnen van het meisje dat lelijk was'* / 'I saw the rabbits of the girl WHO was ugly'), where the relative pronoun is gender-specific, therefore allowing the attachment of the relative clause to be disambiguated at the pronoun. Again, 50% of the primes had a low attachment relative clause structure, 50% of the primes had a high attachment relative clause structure. The sentences were adapted from the materials used by Van de Cavey and Hartsuiker (2016).

A third type of priming sequence consisted of means-end sentences (72 trials per participant), also selected from the materials used by Van de

Cavey and Hartsuiker (2016). In these sentences, dependency relations are formed between parts of a sentence on the basis of preparatory and goal-completing (means-end) actions. For example, the sentence *'Ik geeuwde, nam de telefoon, en belde de manager'* / 'I yawned, took the phone, and called the manager' can be said to contain a means-end dependency between the preparatory action *'I took the phone'* and the completing action *'I called the manager'*. These sentences were all syntactically identical (i.e., they always consisted of three conjoined active transitive clauses), but by manipulating the relative position of the clauses describing the preparatory action and the unrelated action, a HA or LA action sequence structure was created. Once again, 50% of the primes had a HA structure and 50% had a LA structure.

Procedure

All participants were seated in front of a computer, on which the experiment was run. The auditory primes were played to the participants via headphones. The priming sentences were visually presented on the screen. In total, there were 6 trial blocks, 2 blocks per priming condition (music, action goals, and relative clause attachment). The presentation order of the blocks was balanced between participants, and within each block, the trials were randomized for every participant. There were 36 trials within each block, summing up to 216 trials per participant in total.

Each trial began with a fixation cross, followed by a black screen for one second. Then, the screen turned white, and participants either heard the priming pitch sequence through their headphones or read a priming sentence (printed in black, Arial, 18 points, regular) on the screen. After presentation of the prime, the screen turned black again to indicate the target pitch sequence which needed to be responded to. Participants heard the target pitch sequences, followed after two seconds by a blue test screen. Together with this test screen, participants heard a two-pitch probe, and judged whether the two pitches were also presented in that order in the previous pitch sequence by pressing ‘f’ or ‘j’ for ‘fout’(‘wrong’) or ‘juist’ (‘right’) respectively. Then the screen turned black, and after two seconds the following trial started.

Analysis

We ran a mixed models lmer analysis on our data. Our dependent measure was the recognition performance (i.e., proportion of correct responses). In the analysis, we investigated whether the ‘within probe’ advantage (expressed as a contrast for the ‘within’ versus ‘between probes’, denoted as ProbeWithin) interacted with target structure (HA or LA), and region (first or second critical region). This allowed us to check for the expected BPE between structural and superficial boundaries. Furthermore, we added prime structure congruency (congruent or incongruent) as a variable to find possible shifts in processing depending on whether the target structure was congruent with the prime structure. Finally, we also checked for possible differences in our data pattern along the domain in which the prime structures were created (pitch sequences, means-end sentences, and relative clause sentences).

We ran analyses for the trials containing ‘within probes’ and ‘between probes’, to investigate the effects in terms of ‘within probe’ advantage. This entails that we had a 2 (‘within probe’ advantage, expressed as a contrast factor for ‘within probes’ versus ‘between probes’) * 2 (dependency structure of target) *2(region of interest)*2 (prime structure congruency) * 3 (priming domain) design. For each analysis, we also included the years of formal training as a covariate measure. Furthermore, we also analysed the ‘foil probe’ performance separately. The analyses were run on R (version 3.2.3), using the lme4 package (version lme4_1.1-7).

For each analysis, we first determined the optimum lmer model (i.e., the maximal random effects structure justified by the design) by incrementally testing the significant contribution of random slopes over subjects and items to our baseline model (which included only random slopes and all fixed factors). After determining the optimum lmer model, we incrementally added each independent variable to the intercept model, as to derive the best model fit for the data (Bates, Kliegl, Vasishth, & Baayen, 2015). P-values were determined based on the z-values within the glmer model. Also for these analyses, the data files and the corresponding R scripts can be found on http://opensciencework.org/profile/v49bp.

RESULTS

For the data of the 'within probe' advantage, the optimum lmer model included both random intercepts over participant and items, a random slope for probe type and target structure over participant, and probe type, target structure, critical region, and prime structure congruency as fixed factors.

In the general lmer model, we found a significant 'within probe' advantage, expressed in the model as ProbeWithin (β = 1.556, z = 5.671, Pr (>|z|) < .001). Only 53% of the 'between segment' probes were correctly recognized as sequentially occurring pitches in the target sequence, compared to 81% of the 'within segment' probes, a 'within probe' recognition advantage of 28%. Furthermore, there was a three-way interaction between target structure, critical region, and this 'within probe' advantage (β = -1.678, z = -2.540, Pr(>|z|) < .011), showing that the 'within probe' advantage is smaller in the second critical region as compared to the first critical region, but only when the target pitch sequence has a low attachment structure. This is clearly in line with the expected BPE: the second critical region in LA structured sequences contains a superficial boundary, and the 'within probe' advantage should thus be decreased compared to all other critical regions containing a structural boundary.

Furthermore, there was a three-way interaction between the target structure, critical region, and prime structure congruency (β = -1.661, z= -

4.518, Pr(>|z|) < .001), showing that general recognition performance is significantly lower in the second region of LA targets when the prime structure is also congruent as compared to incongruent. As we indeed expected our priming congruency effects to be based on the second critical region (given that only this region contained structure-specific elements), we decided to split up the data for the first and second critical region.

In the second critical region, we found a strong interaction between 'within probe' advantage and target structure (β = 1.661, z = 6.476, Pr(>|z|) < .001), revealing that the 'within probe' advantage was significantly weaker for LA targets as compared to HA targets (see Figure 4). This is expected based on the fact that in the second region, LA structured targets only contain a superficial boundary. Interestingly, there is also a significant interaction between the 'within probe' advantage, target structure, and prime structure congruency (β = 0.842, z = 2.018, Pr(>|z|) = .044), showing that the difference in 'within probe' advantage for HA versus LA structured targets is much more pronounced after an incongruently structured prime as compared to a congruently structured prime. In other words, the data are in line with our expectations of a higher BPE (indicating more thorough processing) in the second critical region when the prime structure is incongruent with the target structure.

Furthermore, in the first critical region, we found a strong 'within probe' advantage of around 34% in all conditions (β = 1.534, z = 5.245, Pr (>|z|) < .001) (see Figure 5). We also found a strong interaction for the overall performance (i.e., both 'within probes' and 'between probes') to be higher for incongruent primes as compared to congruent primes (β = -0.568, z= -3.129, Pr (>|z|) = .002). Descriptively, this increase in recognition performance after incongruent primes seems to stem from a better recognition of 'between probes', or in other words a reduction of the 'within probe' advantage effect (Table 1). However, such claims remain to be further investigated.

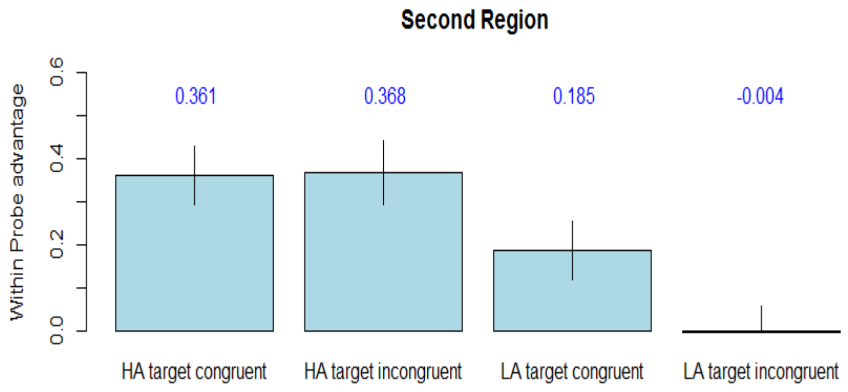

Figure 4: The ‘within probe’ advantage for each condition in the second critical region. Confidence intervals (95%) were derived from the optimum lmer model with crossed random effects

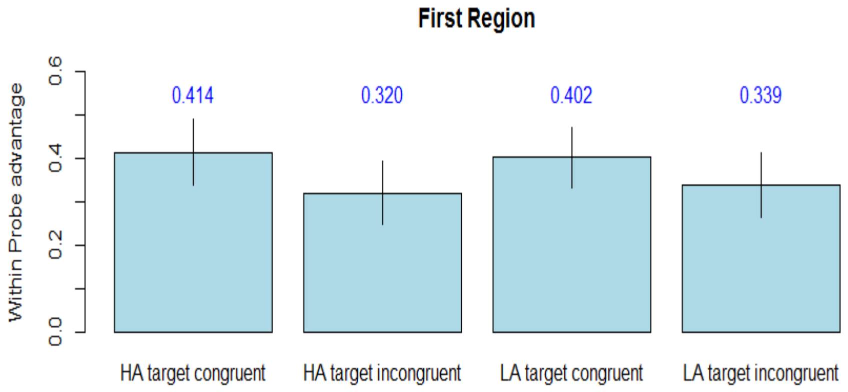

Figure 5: Overview of the ‘within probe’ advantage for each condition in the first critical region. Confidence intervals (95%) were derived from the optimum lmer model with crossed random effects

	First Critical Region				Second Critical Region			
Prime	High Attachment		Low Attachment		High Attachment		Low Attachment	
Target	HA	LA	HA	LA	HA	LA	HA	LA
Between Probe	37.79% ***(7.7%)***	48.45% ***(8.2%)***	51.58% ***(8.4%)***	46.17% ***(8.1%)***	49.91% ***(7.7%)***	81.90% ***(6%)***	42.95% ***(7.4%)***	64.36% ***(7.5%)***
Within Probe	79.19% ***(8.1%)***	82.35% ***(7.5%)***	83.58% ***(7.2%)***	86.37% ***(6.6%)***	86.03% ***(6.7%)***	81.46% ***(7.7%)***	79.77% ***(8%)***	82.92% ***(7.4%)***
Foil Probe	65.33% ***(9.8%)***	67.51% ***(9.6%)***	53.58% ***(10.1%)***	62.82% ***(9.9%)***	49.73% ***(10.8%)***	66.32% ***(10.5%)***	53.51% ***(10.9%)***	60.76% ***(10.8%)***

Table 1: Overview of the % of correct responses over target structure, prime structure, and critical region. Between brackets, you can find the distances to the 95 % confidence interval.

Importantly, throughout our analyses, the domain in which the prime structures were created never provided a significant contribution to the model. This is in line with earlier findings (Van de Cavey & Hartsuiker, 2016) of relatively domain-general priming effects. Nevertheless, we also split up the data to look at the priming effects within each domain.

For the attachment prime structures, we find a significant ‘within probe’ advantage (β = 1.691, z = 4.283, Pr (>|z|) < .001). Furthermore, we found a three-way interaction between probe structure congruency, critical region, and target structure (β = -1.464, z = -2.372, Pr(>|z|) = .02), showing a higher general performance for LA targets in the second region when the prime structure was incongruent as compared to when the prime structure was congruent. Furthermore, a marginally significant three-way interaction between the ‘within probe’ advantage, target structure and critical region (β = -1.453, z = -1.634, Pr (>|z|) = .102), revealed our expected BPE for structural as opposed to superficial boundaries.

For the means-end prime structures, we find a similar pattern. There is a strong ‘within probe’ advantage (β = 1.771, z = 4.496, Pr (>|z|) < .001), and a significant three-way interaction between the ‘within probe’ advantage, target structure, and critical region (β = -2.368, z = -2.887, Pr (>|z|) < .01).

Here too, we find a three-way interaction between target structure, prime structure congruency, and critical region (β = -1.947, z = -3.009, Pr (>|z|) = .003). The decreased 'within probe' advantage for incongruent prime structures on the second region of LA targets is marginally significant for means-end prime structures (β = 1.861, z = 1.840, Pr (>|z|) = .066).

For the pitch sequence primes, we again find a strong 'within probe' advantage (β = 1.387, z = 3.069, Pr (>|z|) = .002). Furthermore, we find effects of incongruent prime structures increasing overall performance for the second critical region of LA targets (β = 1.806, z = 2.958, Pr (>|z|) = .003) as compared to HA targets. Overall, as represented in Table 2, we can state that the aggregated data patterns are very similar for each domain, though within-domain priming (i.e., from pitch sequence primes to pitch sequence targets) is slightly stronger as compared to cross-domain priming.

	First Critical Region				Second Critical Region			
Prime structure	High Attachment		Low Attachment		High Attachment		Low Attachment	
Target structure	HA	LA	HA	LA	HA	LA	HA	LA
Pitch sequence	39.69% ***(10.6%)***	26.37% ***(10.9%)***	26.70% ***(10.6%)***	45.08% ***(9.0%)***	32.62% ***(9.8%)***	0.32% ***(8.9%)***	31.85% ***(10.9%)***	19.33% ***(9.9%)***
Means-end sequence	42.21% ***(10.7%)***	34.37% ***(10.8%)***	34.44% ***(9.9%)***	41.23% ***(10.4%)***	35.13% ***(10.1%)***	-9.63% ***(8.9%)***	43.28% ***(10.1%)***	20.22% ***(9.2%)***
Attach-ment sequence	42.26% ***(10.8%)***	40.89% ***(9.6%)***	34.85% ***(10.5%)***	34.22% ***(10.1%)***	40.58% ***(9.5%)***	8.03% ***(8.9%)***	35.31% ***(10.6%)***	16.04% ***(10.5%)***

Table 2: Overview of the 'within probe' advantage over target structure, prime structure, and domain of priming. Between brackets, you can find the distances to the 95 % confidence interval.

Finally, we also considered the performance on the foil probes. Here, we find an interaction between prime structure congruency and target structure (β = -0.701, z = -2.665, Pr (>|z|) = .008), showing that recognition performance (i.e., correct rejection) for the foil probes is better for LA targets, unless the prime structure is incongruent. An interaction between critical region and prime structure congruency (β = -0.637, z = -2.468, Pr (>|z|) = .014) also reveals an effect for recognition performance to be slightly better in the second critical region for congruent primes. Furthermore, experience with music or year of formal music training did not influence our results, as can be expected based on the novelty of the pitch sequence structures.

DISCUSSION

In the current study, we aimed to address whether cross-domain priming (Scheepers et al., 2011; Van de Cavey & Hartsuiker, 2016) could be extended from influences on the completion of written materials to influences on the implicit processing of simple auditory sequences. We therefore created simple pitch sequences containing either structural boundaries or superficial frequency shifts in two critical regions. In light of a previous study by Tan et al. (1981), we expected participants to process the integrational structure of the pitch sequence based on the structural but not the superficial boundaries. This is indeed what we found: the ‘within probe’ advantage effect (i.e., the extent to which the recognition performance is influenced by a segmented representation of the sequence along this boundary) was considerably larger for structural as opposed to superficial boundaries. This idea, that ‘within probe’ advantage interacts with the extent to which a boundary is processed, is what we called the Boundary Processing Effect (BPE). We argue that this difference in ‘within probe’ advantage for structural versus superficial boundaries supports our claim that participants do indeed process the implicit structure of the pitch sequence.

Furthermore, we assured that while all our pitch sequences contained a structural boundary in the first critical region, only half contained a structural boundary in the second critical region (the other half contained only a superficial boundary in the second critical region). Importantly, a structural boundary in the second critical region would induce a long dependency in the target pitch sequence structure, similar to a high attachment structure, whereas a superficial boundary in the second region would be similar to a low attachment structure. To investigate whether the processing of our pitch sequences (as measured through the BPE) could be influenced by prime structures across domains, we presented three priming conditions, using structural priming materials from Van de Cavey and Hartsuiker's (2016) experiment: relative clause sentences, means-end sentences, and pitch sequences.

We expected that, specifically in the second critical region of our pitch sequences, structural processing might be influenced by whether or not this second critical region contained elements which were expected based on the prime structure. Indeed, we found a higher BPE when comparing structural to superficial boundaries in target regions which were incongruent with the prime structure. As explained in the introduction, we take this higher BPE to indicate that the melody is more strongly parsed along the structural as opposed to superficial boundaries (and thus is processed more accurately). In other words, we suggest a more accurate processing of the pitch sequence structure in regions that were unexpected based on the prime structure. This indicates a more thorough processing of such unexpectancies, as is supported by the finding of a slightly decreased 'within probe' advantage for the structural boundaries in the first critical boundary. Importantly, this pattern was found across all three priming domains.

In summary, we can conclude the following. First, through our offline recognition measure, we were able to discern to what extent participants processed implicit structural boundaries in simple pitch sequences. Furthermore, we find that after presentation of a structural prime, there are clear behavioural markers of a more thorough processing of structural elements which are incongruent with the prime structure. This clearly suggests that earlier cross-domain priming effects (Van de Cavey & Hartsuiker, 2016) are not limited to explicit, verbal processing, but can also be found in more low-level structural processing. Therefore, we take these findings as support for the idea that cross-domain priming effects are being based on low-level, structural processing mechanisms such as structural prediction, and cannot be attributed to conscious strategies or analogical reasoning.

It is important to note that, whereas within-domain priming structures (pitch sequences) caused larger congruency effects, the congruency pattern was present also for the between-domain priming structures (relative clause and means-end sentences). However, the dissociation of within and between domain priming effects needs to be further addressed in future research (which has sufficient power to significantly capture all possible differences). For now, the essential contribution is that structural processing of musical sequences *can* be accurately measured, and *does* portray structural priming effects, at least within the auditory domain.

CONCLUSION

The goal of the current study was to directly address whether recent cross-domain priming effects (e.g., Scheepers & Sturt, 2014; Van de Cavey & Hartsuiker, 2016) can be replicated also using a measure of implicit structural processing, rather than explicit verbal responses. We adapted three priming domains from an earlier study by Van de Cavey & Hartsuiker (2016), namely high versus low attachment structured pitch sequences, action descriptions, and relative clause sentences. In contrast to earlier research however, we measured priming effects upon the implicit structural processing of simple auditory sequences. Following a recognition task, our data suggest a more thorough processing of boundaries in the target pitch sequences when those boundaries were unexpected based on the integrational structure of the preceding prime. This suggests a resource allocation based on structural predictions from prime structures. Furthermore, whereas the primes constructed in the non-linguistic domain revealed clear priming effects, the primes created in the linguistic domains showed decreased, but very similar priming effects, supporting the idea that the found structural priming might not have a domain-specific ground. Whereas the differences between priming domains remains to be further investigated, the current study thus shows that applying structural priming paradigms within and between domains on the structural processing of non-linguistic materials is both possible and fruitful.

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CHAPTER 6
GENERAL DISCUSSION

The research presented in this doctoral dissertation aims to provide a contribution to the ongoing debate on overlap in structural processing across content domains. Whereas it is generally assumed in cognitive research that structural processing is functionally specified along content domains (e.g., linguistic syntax, musical harmony, and mathematic equations), this assumption of domain-specificity has been somewhat challenged in recent years (Patel, 2008, Kljajevic, 2010; Slevc & Okada, 2015).

Of course, it must be acknowledged that structural rules are different across content domains (e.g., ‘nouns’ and ‘clauses’ in language, ‘keys’ and ‘tonic’ in music), and that in relation to this, domain-specific networks seem to support structure processing (see Alossa & Castelli, 2009; Fedorenko, Behr & Kanwisher, 2011; Fedorenko, McDermott, Norman-Haignere, & Kanwisher, 2012). However, it can be noted that the structural processing mechanisms, as they are modelled across content domains, contain strong similarities. In both language and music, structural integration is said to be governed by dependency processing (Dependency Locality Theory, Gibson, 2000; Tonal Pitch Space, Lerdahl, 2001) and expectancy generation (Levy, 2008; Wiggins, 2011). Furthermore, from an evolutionary (Cross, 2011), developmental (Brandt, Gebrian & Slevc, 2012) and neurophysiological (Sammler et al., 2013) perspective, clear similarities are found when comparing structural processing across content domains.

In the past decade, several models have been developed which address the question of domain-generality in structural processing by making a distinction between structural rule representations, and the resources and mechanisms which support a structural processing on the basis of such representations. These ‘resource sharing’ models (Shared Syntactic Integration Resource Hypothesis, SSIRH, Patel, 2003; Syntactic Working Memory, SWM, Kljajevic, 2010) suggest that structural rule representation networks are of course specified between content domains, and thus might be at the root of neuronally distinct regions. However, the similarity in the structural processing functions across domains might entail that the resources supporting structural processing are domain-general. As an example, listening to sentences or melodies is quite different with respect to the structural rules (linguistic syntax, tonal harmony) by which they are interpreted, but the process of applying these rules to structurally process the incoming information (i.e., processing the relationship between elements, creating expectations about upcoming elements) is similar and thus might make an appeal on domain-general resources.

Following the development of ‘resource sharing’ models, several studies have addressed the hypothesis that interference should be observed when high structural processing demands are simultaneously encountered in the processing of materials across domains. After all, a high structural processing demand in one domain (e.g., processing an ‘out-of-key’ chord in a melody) should deplete domain-general structure processing resources, which would impede simultaneous structural processing of other materials (e.g., simultaneously reading a ‘garden path’ sentence like: *‘the horse raced past the barn fell’*).

Such interference during the simultaneous processing of structural difficulties in materials across domains has indeed been found. For example, Slevc, Rosenberg and Patel (2009) asked participants to read sentences containing either syntactic ‘garden path’ difficulties (‘the lawyer advised the defendant *was guilty*’) or semantic unexpectancies (‘the boss warned the mailman to watch out for angry *dogs* when delivering mail’). All sentences were read in a self-paced presentation of segments, and were accompanied by chord sequences. Slevc et al. (2009) found that providing ‘out-of-key’ chords together with syntactic ‘garden path’ words (but not semantically unexpected words) further increased reading times. This can be taken as evidence for interference during the joint provision of structural difficulties across domains

, in favour of the abovementioned 'resource sharing' models. Similar findings of interference during the joint processing of structural difficulties across domains have repeatedly been shown (e.g., Hoch, Poulin-Charronnat, & Tillman, 2011).

Nevertheless, there are some limitations to previous research supporting the idea of overlapping resources for structural processing across content domains (Slevc & Okada, 2015). Most evidence in favour of such 'resource sharing' models stems from interference during the simultaneous processing of structural difficulties across domains, which is measured on general performance tasks like reading times and comprehension accuracies (e.g., Slevc et al., 2009). There might be some issues with using such paradigms.

First, as previous research has mainly made use of general linguistic performance measures, the interpretation of the found interference effects is mainly relying on the contrasting of experimental conditions. For example, in the abovementioned study of Slevc et al. (2009), reading times are only related to structural processing through the contrasting of the 'syntactic garden path' condition to the 'semantic violation' condition. A similar contrasting of experimental conditions is used in EEG studies, to elicit event-related potentials which can be brought back to structural processing. The problem with such contrasts however is that the interpretation of differences between conditions is largely dependent on the accuracy with which those conditions are matched. For example, in relation to the example of Slevc et al. (2009), recent studies (Perruchet & Poulin-Charronnat, 2013) have argued that the provision of 'garden path' sentences versus semantic violations might differ not only in the structural nature of the unexpectancy, but might also entail differences in the amount of attention allocation. As recently stated by Hoch et al. (2011), the use of experimental contrasts to drive structural processing effects from general processing measures proves to be a difficult challenge.

Second, joint processing paradigms are focused on studying the effects of the simultaneous processing of structural difficulties across domains (e.g., Hoch et al., 2011). Though such paradigms are well-suited to investigate the hypothesis of ‘resource sharing’ models, their ecological validity is quite low. In real life, participants rarely encounter structural violations in (often pre-recorded) melodies, let alone that such harmonic violations would be presented simultaneously with structural unexpectancies in other domains. Therefore, the question can be raised to what extent interactions in structural processing across domains can also be found using paradigms and materials with a higher ecological validity.

Current Research. To address the abovementioned concern with the use of experimental contrasts to study structural processing in linguistic domains, the current dissertation focused on a non-linguistic measure of structural processing. Investigating the influences of structural processing in language on non-linguistic processing is not only relevant to address the assumed bi-directionality of resource sharing (SSIRH, Patel, 2003; SWM, Kljajevic, 2010), but furthermore might also allow for a more direct measurement of structural processing. After all, in non-linguistic materials like music, there is no semantic or thematic component which can confound processing measures, as opposed to language (Patel, 2008). In the current dissertation, we developed experimentally structured pitch sequences, the structural processing of which could be directly related to a recognition task effect (Tan, Aiello & Bever, 1981). On the basis of these newly developed materials and measures, we addressed the previous joint processing interference findings (e.g., Slevc et al., 2009), through a structural processing measure that could be directly related to structural processing (as opposed to a general measure which was then compared between experimental conditions to infer structural processing). In this way, recent concerns on the matching of experimental conditions (Perruchet & Poulin-Charronnat, 2013) can be addressed. This has been elaborated upon in the study presented in Chapter 2.

To address the abovementioned concern on the ecological validity of the interference findings in joint structural processing paradigms, we investigated to what extent interactions in structural processing across domains could be found in a more naturalistic setting. For this, we largely based ourselves on recent cross-domain priming findings (e.g., Scheepers, Sturt, Martin, Myachykov, Teevan, & Viskupova, 2011; Scheepers & Sturt, 2014), which suggest that interactions in the structural processing of materials across domains can also be found when studying the sequential processing of well-structured materials. This has been elaborated upon in Chapters 3, 4 and 5.

In this general discussion, we will first summarise the research chapters. Then we turn to the perspectives our findings offer for current models of domain-generality in structural processing, and elaborate on implications our research might have for theoretical approaches in psycholinguistics as well as other domains of cognition. We end with a critical discussion of the limitations of the discussed research, suggestions for future research, and the general conclusion of this dissertation.

RESEARCH CHAPTERS

Shared Structuring Resources: Joint Processing Interference

The first study, which is reported in Chapter 2, addresses the recent debate that has risen on the interpretation of previously found interference effects during the joint processing of structural difficulties. As has been mentioned earlier, the fact that previous measures on which such interference was found (e.g., reading times, Slevc et al., 2009) measure general performance rather than specific structural processing effects, entails that previous research has been largely dependent on a matching of experimental conditions to yield an indication of structural processing, which makes it difficult to exclude other interpretations for the interference (Perruchet & Poulin-Charronnat, 2013). Our newly developed recognition task measure can provide a valuable perspective in this debate, as it allows for a measure that specifically taps into structural processing.

In the study reported in Chapter 2, we provided participants with a double-task paradigm in which they read sentences while listening to the experimentally manipulated pitch sequences. Half of the sentences were control sentences, which contained a passive complement clause (e.g., ‘Zeg de dokter dat zijn zoon ontvangen *wordt* in de hal’, translated as ‘Tell the doctor that his son [received *is*] in the hallway’). However, 25% of the sentences contained a word class error (e.g., ‘Vraag de directeur of de dossiers gehaald *plek* door de secretaris’, translated as ‘Ask the director if the files [fetched *place*] by the secretary, where *place* is a noun instead of the expected auxiliary verb). Such word class errors cannot be resolved into a syntactically correct sentence. The remaining 25% of the sentences contained a structural ‘garden path’, in which the complement clause did not have the expected passive voice (e.g., ‘Vraag de agent of de inbreker onderschept *welke* berichten er zijn’, translated as ‘Ask the policeman if the burglar [caught *which*] messages there are’) but was otherwise a syntactically correct sentence. Sentences were visually presented in segments, and each segment was combined with a pitch, so that a pitch sequence was heard while the sentence was being read at a fixed pace. A pitch cluster boundary was presented either simultaneously with the sentential unexpectancy or not, and interestingly, using the pitch recognition task it was found that the ‘within probe’ advantage, measuring structural parsing along this pitch cluster boundary, was found in all conditions except when the boundary was presented simultaneously with a ‘garden path’ unexpectancy in the sentence.

In other words, specifically for the condition in which a sentential unexpectancy was presented which incites structural reintegration (i.e., a ‘garden path’ unexpectancy) simultaneously with the presentation of a pitch cluster boundary (which incites structural integration of the pitch sequence), it was found that this pitch cluster boundary was processed to a lesser extent (as measured through the ‘within probe’ advantage in an off-line recognition measure). This suggest that a high demand on structural processing resources in one domain (sentences) can interference with simultaneous structural processing in another domain (pitch sequences), thus supporting the idea of ‘resource sharing’ models (SWM, Kljajevic, 2010). Moreover, given that the interference was measured by a specific boundary processing effect on the recognition task, rather than general recognition performance, some alternative explanations for previous interference findings (Perruchet & Poulin-Charronnat, 2013) can be excluded.

Shared Structuring Resources: EEG Paradigm

One limitation of the abovementioned study is that the use of joint processing paradigms is still quite far from being naturalistic. This is to say, interference has mostly been found upon the provision of structural difficulties (e.g., ‘garden path’ manipulations) in one domain simultaneously with the provision of critical elements in the structural processing of another domain. This might be very hard to generalize to our daily functioning, or possible applications of such resource overlap.

With this in mind, the study reported in Chapter 3 aspired to address to what extent interactions between structural processing across domains could be obtained when (a) working with non-erroneous materials and (b) using a non-simultaneous provision of critical points in structural processing. To investigate this, we provided participants with a double-task paradigm, in which they had to read Dutch relative clause sentences (Scheepers, 2003). These sentences lend themselves to creating more than one integrational structure, while otherwise being completely naturalistic and similar. The difference between both forms of relative clause sentences in our study could be summarized as whether the relative clause had a high attachment to the main clause (e.g., *‘I see lights of the room that are bright’*), or a low attachment to the prepositional clause (e.g., ‘*I see the lights of the room that is bright’*). This attachment structure could also be mimicked by creating structural boundaries in the pitch sequences which did or did not instigate a return to the root of the pitch sequence (e.g., *‘ABE|CGF|AB’* for high attachment, or *‘ABE|CGFCG’* for low attachment). Recent evidence in psycholinguistics (e.g., Scheepers et al., 2011) seems to suggest that interactions in the processing of attachment structure can be found during the sequential processing of linguistic and non-linguistic materials.

Therefore, in the study reported in Chapter 3, we separated the points of structural disambiguation for the relative clause sentences and the pitch sequences, so that structural processing of both materials would not occur simultaneously. More specifically, we ran an EEG experiment, in which we provided participants with relative clause sentences while listening to pitch sequences. All relative clause sentences were disambiguated very late in the presentation of the sentence, after the integrational structure of the pitch sequence was already apparent. If it were true that the domain-generality of structural processing is only limited to on-line interference, then, as Chapter 2 showed, the temporal mismatch between the structural disambiguation of both materials should prevent any interactions between domains from occurring.

However, given that we manipulated the attachment structurel of the accompanying pitch sequence to be congruent with the later disambiguated relative clause sentence in the vast majority (80%) of the cases, we argued that the structure of the pitch sequence might influence structural predictions for the disambiguation of the sentence structure. Even though sentences in both attachment structures were structurally sound, we found (structural) unexpectancy processing components (P2, P3, LAN, P600) when the sentential disambiguation was both less preferred (HA sentences), and also did not match what would be expected based on the integrational structure of the pitch sequence.

This finding of structural reintegration components on the basis of an interaction between linguistic preferences and structural congruency of preceding non-linguistic materials strongly suggests that even during the processing of non-erroneous materials (which furthermore are not overlapping in on-line processing requirements) interactions across content domains can be found.

Cross-Domain Structural Priming to Production

The study reported in Chapter 3 seems to suggest that even when stimuli from two domains are presented non-simultaneously, some cross-domain interactions can still occur. This is interesting in the light of recent findings of attachment priming, which seem to stretch beyond linguistic syntax structures and perhaps even content domains (Scheepers, 2003; Desmet & Declercq, 2006; Scheepers et al., 2011). The studies reported in Chapter 4 therefore addressed to what extent recent findings of cross-domain attachment priming (Scheepers et al., 2011, Scheepers & Sturt, 2014) could be replicated and extended to other domains, such as the pitch sequences used in the previous studies.

Similar to the structural priming paradigm that was used in previous psycholinguistic studies (Scheepers et al., 2011), we presented our pitch sequences as a structural prime to the completion of an open-ended relative clause sentence (e.g., *'I see the lights of the room that…'*). The pitch sequences did or did not include a dependency to the root (e.g., *'ABA|CGF|EB'* for high attachment sequences, as compared to *'ABA|CFGGC'* for low attachment pitch sequences), which primed the participants' preferred structure in the subsequent sentence completion task. Importantly, no such priming effect could be observed when using a colour sequence prime, which had a similar order, but could not induce dependency relationships. This confirmed that the priming effect was based on integrational dependency structure, rather than a likeness in parsing.

Furthermore, a large follow-up experiment did not only replicate the finding that pitch sequence structures could prime structural choices in language, but also found priming effects for similarly structured math equations (e.g., *'80–(9+(1x5))'* corresponds to an LA structure, whereas *'80–((9+1)x5)'* corresponds to an HA structure, see Scheepers et al., 2011). Also, we found that goal-directed action descriptions (e.g., *'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, see Allen, Ibara, Seymour, Cordova, & Botvinick, 2010) could also prime relative clause completion, as well as be primed by all previously mentioned materials. This series of experiments thus clearly indicates that the production of linguistic information, albeit structured by syntactic or action-goal dependencies, can be influenced by the structural processing of preceding information across several domains.

Cross-Domain Structural Priming to Comprehension

Chapter 5 reports a study that was aimed at further addressing the nature of the priming effects which have been reported in recent years (Scheepers et al., 2011; Scheepers & Sturt, 2014) and have been replicated and extended in Chapter 4.

In a preliminary experiment (which can be found in Appendix 1), we investigated whether the priming effects from pitch sequences to sentence completion as reported in Chapter 4 could be replicated on the basis of structural parsing. For this, pitch sequences were created which mimicked the parsing boundaries of high dependency structures, but not their dependency relationship (e.g., a second pitch cluster shift which entailed a transition to a third pitch cluster, rather than a return to the root pitch cluster, thus being similar to HA pitch sequences in the ordering of pitch cluster transitions, but not their dependency structure). It was found that such materials did not elicit priming effects. Therefore, in relation to the colour control experiment reported in Chapter 4, we argue that the priming effects can be related to something inherent to the dependency structure, rather than order or parsing structure, of our materials.

Another interesting element in the cross-domain priming findings that were reported in Chapter 4 is that all priming effects were measured by the explicit completion of structured, written materials. To address whether the cross-domain priming effects are truly related on a level of (implicit) structural processing as compared to more explicit strategies, we found it important to test whether cross-domain priming effects can also be observed in the processing of non-linguistic, implicitly structured information.

With this in mind, a structural priming study was done on the basis of the priming materials used in Chapter 4. However, instead of measuring priming effects of these materials on explicit linguistic continuations, we investigated whether a processing of these priming materials might influence the structural processing of subsequent pitch sequences, as measured by our recognition task measure. The study revealed that the integrational structure of preceding pitch sequences, as well as the integrational structure of preceding relative clause sentences and goal-directed action descriptions, could alter the structural integration of following pitch sequences. Not only does this replicate the finding of cross-domain priming on a novel domain, but furthermore it confirms that this form of structural priming can be driven by implicit mechanisms of integrational dependency processing.

We now turn to the perspectives that the research reported in this dissertation brings to the current debate on domain-generality of structural processing.

PERSPECTIVES ON THE CURRENT STUDIES

‘Resource Sharing’ Models: what drives joint processing interference?

A first goal of the studies reported in this dissertation was to provide a novel perspective on previous findings of interference during the joint processing of structural difficulties across content domains. In recent years, there has been an ongoing debate (e.g., Slevc & Okada, 2015) on the interpretation of such interference findings. Although they seem to support the idea of a domain-general pool of structural processing resources, they are largely based on a contrasting of experimental conditions (e.g., structural unexpectancies as opposed to semantic violations), so that the interpretation of the interference findings is hindered by possible confounds in contrasting (see Perruchet & Poulin-Charronnat, 2013).

The study presented in Chapter 2 reports interference from a simultaneous processing of structural integration difficulties in language on the structural processing of pitch sequences. In contrast to previous studies, the dependent measure here was not general linguistic performance, but rather specific structural parsing effects in an off-line recognition task. Because of this, the found interference could be directly related to the process of structural parsing in a well-structured auditory sequence, which argues in favour of such interference being based on an overlap in structural processing resources (Kljajevic, 2010), rather than attentional effects arising from the contrasting of conditions (Perruchet & Poulin-Charronnat, 2013).

Furthermore, the finding of interference during the joint structural processing of sentences and our experimentally manipulated pitch sequences, seems to provide further evidence in favour of ‘resource sharing’ models which consider an overlap in general resources supporting structure processing (e.g., Syntactic Working Memory, Kljajevic, 2010), rather than an overlap in ‘syntactic’ processing resources (e.g., Shared Syntactic Integration Resource Hypothesis, Patel, 2003). After all, the pitch sequences that were used in Chapter 2 did not follow tonal harmony, but rather a simple pitch clustering. It thus seems quite far-fetched to suggest that the interference between linguistic and non-linguistic structural processing found in Chapter 2 is obtained through a sharedness of syntax specific resources, rather than more general (working memory, Kljajevic, 2010; cognitive control, Slevc, Reitman & Okada, 2013) cognitive resources. In the following segments, we will shortly sketch suggestions for domain-general resource pools which might aid structural processing across domains (working memory, implicit learning, and cognitive control). It is important to notice that these accounts are not mutually exclusive, and that they can be regarded as largely overlapping (see Slevc & Okada, 2015).

Working Memory Resources. One concept that unifies the structural processing of previously used materials (syntactically complex sentences, semantically complex sentences, harmonically complex melodies, and our experimental pitch sequences), is that in the study of structural processing in all these domains, the assumption is made that structural integrations are more costly over long dependencies. This relates to the idea that working memory resources (implied in representing previously heard materials and integrating novel elements into this representation) are of high importance in the structural processing across domains (e.g., Gibson, 1998). In language (Lewis, Vasishth & Van Dyke, 2006), but also in music (Koelsch, Schulze, Sammler, Fritz, Muller & Gruber, 2009), working memory is seen as a key feature of structural processing. Furthermore, working memory is associated with the frontal regions which are typically implied in the overlap found during joint processing tasks (Koelsch et al., 2009; Schulze, Zysset, Mueller, Friederici, & Koelsch, 2011). As has been mentioned in the introduction of this dissertation, recent ‘resource sharing’ models have been developed on the idea of working memory resources (Kljajevic, 2010), and have been corroborated in joint processing studies (Fiveash & Pammer, 2012).

Implicit Learning Accounts. Another element that is present in structural processing theories across several domains and materials, is implicit learning. As has been discussed in the introduction, implicit learning can be defined as the capacity people have to acquire and apply regularities on the basis of prior exposure to a certain type of information. For both linguistic and non-linguistic materials (e.g., music), implicit learning is seen as a key feature in syntax learning and application. In favour of the idea that resources involved in implicit learning might be shared across content domains, several studies have shown that structural training in one domain can improve the speed of implicit learning (and application) of structural rules in another domain (Jentschke & Koelsch, 2009; Francois & Schön, 2011). A recent review paper by Ettlinger, Margulis and Wong (2011) emphasizes the role that implicit learning has on the processing of linguistic as well as musical stimuli, and discusses their associated neural structures. These researchers state that when investigating language processing, music processing, or implicit learning, there is a wide range of similarities in what cognitive functions are being employed (sequential learning, expectation generation) and with it, in the neural regions that are related to such cognitive functions (mainly the fronto-striatal system). Therefore, the concept of implicit learning might be of great value in conceptualizing the nature of domain-general structural processing resources.

Cognitive Control Accounts. More recently, the idea of shared resources for structural processing across domains has also been directed towards the idea of cognitive control (Slevc & Okada, 2015). On the basis of the idea that expectancy generation is of paramount importance in structural processing across domains (Levy, 2008), incoming elements which are inconsistent with the predictions might instigate cognitive control processes, regardless of the content domain in which this unexpectancy occurs. In favour of this idea, Slevc et al. (2013) approached non-linguistic interference on linguistic processing by means of Stroop-task paradigms, which suggests that it might be the amount of cognitive control (i.e. unexpectancy detection and resolution) required for structural unexpectancy resolution that drives interactions in processing across domains. In fact, several of the brain regions typically found when investigating structural unexpectancy processing (frontal regions, Broca's area) across domains have also often been linked to cognitive control (Miller & Cohen, 2001). Especially given the point (as mentioned earlier) that current findings of joint processing interference like the results reported in Chapter 2 are based on the provision of structural difficulties across domains, it cannot be denied that cognitive control and error monitoring might be important in the conceptualisation of 'resource sharing' accounts.

‘Resource Sharing’ Models: interactions beyond on-line processing?

A second goal of the studies reported in this dissertation was to assess to how interactions in joint structural processing paradigms (as mentioned above) relate to more ecologically valid situations. After all, ‘resource based’ models (regardless of how these resources are conceptualized) make the hypothesis that structural processing across domains would only interact when a high demand on such resources would be made simultaneously. However, the simultaneous presentation of structural difficulties across materials is rather unnaturalistic. If overlap in structural processing across domains does not stretch beyond these highly experimental conditions, what implications might such findings have? Interestingly, recent structural priming evidence in psycholinguistics (Scheepers et al., 2011; Scheepers & Sturt, 2014) suggests that cross domain influences can also be observed in the sequential (rather than the joint) processing of materials. Based on these recent findings, we have developed several studies investigating possible interactions in the sequential processing of linguistic and non-linguistic materials.

In Chapter 3, we have reported an EEG study examining the possibility of interactions in structural processing across domains when studying the sequential processing of well-structured materials. We found that several event-related potentials relating to structural unexpectancy processing (P2, P3, LAN, P600) were elicited more strongly when a sentential disambiguation was provided that was not only less preferred, but also unexpected on the basis of an earlier non-linguistic structural disambiguation. In Chapter 4, we reported structural priming findings, showing that the attachment choice in relative clause completions could be primed not only by preceding mathematical equations (see Scheepers et al., 2011), but also our structured pitch sequences and even linguistic action descriptions. Control experiments showed that such priming findings were not based on sequential order, but on the integrational structure of the used materials. In Chapter 5, we report findings indicating that cross-domain structural priming can also be observed on the perception of implicitly structured pitch sequences. In sum, all these studies suggest that interactions in structural processing across domains extend to sequential processing of ecologically valid, well-structured materials.

Importantly, such findings are not in line with the hypotheses of ‘resource based’ models. After all, following a sequential processing of materials across domains, there is no on-line competition in the demand for shared structural processing resources. Therefore, even recent interpretations of domain-general resources in terms of working memory and cognitive control have been tested under the assumption that only on-line interactions in structural processing across domains can be found. In other words, our findings (especially concerning structural priming) demand an explanation beyond what would currently be hypothesized by ‘resource sharing’ models.

Structural Priming: Competing accounts

How can our cross-domain structural priming effects be interpreted? A valuable perspective is offered in previous papers on such structural priming findings (Scheepers et al., 2011). In this research, two competing explanations have been suggested.

Representational account. The first explanation can be summarized as the ‘representational’ account. This account suggests that, at some level of abstraction, a global configuration can be retained, which is domain-general. In other words, one could argue that structural attachment priming (Scheepers, 2003) can be modelled similarly to other forms of structural priming (see Pickering & Branigan, 1998), namely through an activation of some kind of abstract syntactic representation. In contrast to the language-specific syntax representations suggested by other priming accounts though (Pickering & Branigan, 1998), attachment priming might be based on more abstract structural representations which are not language-specific. This might then explain why non-linguistic information (such as the arithmetic equations used in Scheepers et al., 2011) could prime attachment completion in language: for both domains, the same abstract structural representation is activated.

Importantly, this account does not make any assumptions about the way in which sequential elements (for example mathematical equations) are processed: all that matters is the hierarchical representation which is activated upon processing.

This representational account does not seem to fit with more recent cross-domain priming evidence, however. Scheepers and Sturt (2014) found that left-branching or right-branching mathematical equations (e.g., *'3+2*5'* as right-branched versus *'3*2+5'* as left-branched) could prime the plausibility judgement of left-branching versus right-branching adjective-noun-noun compounds (e.g., 'divorced *hospital nurse'* as right-branched versus '*dental hospital* nurse' as left-branched). They furthermore found that the extent of the cross-domain priming was dependent on the structural complexity of the targets (i.e., right-branching mathematical equations being harder to solve and thus having more priming effects from preceding adjective-noun-noun compounds). The priming effects of Scheepers and Sturt (2014) thus falsify the representational account for cross domain structural priming. After all, right-branched and left-branched equations (e.g., *'3+4*4'* or *'3*4+4'* respectively) might differ in the point of computational complexity, but have the same hierarchical structure (as opposed to *'3+(4+4)*5'* versus *'3+4+4*5'* which has a different bracket hierarchy,see Scheepers et al., 2011). Priming effects are *not* simply dependent on an abstract hierarchical representation (as created through sentential syntax or mathematical structure); the incremental processing of the materials (left to right or vice versa) does seem to matter.

The findings that are presented in this dissertation also seem to mismatch a representational account for cross-domain structural priming. By extending the cross-domain priming findings in previous research to materials like our auditory pitch sequences and goal-directed action descriptions, it seems very unlikely that there is a general structural representation which is activated across all domains. After all, both the action descriptions and the pitch sequences do not have a stringent representational pattern. The action descriptions follow a non-syntactic thematic structure, and the pitch sequences follow a pitch cluster transition, both of which might be hard to relate to the stringent syntax by which hierarchical representations in mathematics or language are created. As has been mentioned in the introduction, it is important to note that whereas headed hierarchies (e.g., tree structures) can be created in both language and music, both domains differ in their rigidity (Lerdahl, 2013). For example: an adjective relates to a noun following categorical linguistic rules, which is much more stringent than a relationship a tone might have to its tonic. In sum, the idea of a 'representational' account for structural priming seems to fit poorly with both recent cross-domain priming findings (Scheepers & Sturt, 2014) as well as with the priming findings that have been reported in the current dissertation.

Incremental-Procedural Account. The incremental-procedural account for cross domain structural priming (as developed in Scheepers et al., 2011, and extended by Scheepers & Sturt, 2014) entails that sequential processing of both the relative clause sentences and the arithmetic equations used in previous cross domain priming studies (Scheepers et al. 2011; Scheepers & Sturt, 2014) entails a left-to-right reading. Hence, in the processing of arithmetic equations like *'3+(2–2)x5'*, similar to relative clause sentences like *'I see the lights of the room that is wide'*, participants are incrementally processing the sequential information, and the structural complexities involved in high attachment versus low attachment structures are encountered in a similar incremental processing across domains.

Following the incremental processing, the difference in relative clause structures as well as in the arithmetic equations can be related to whether the final element combines with a simple (LA) or more complex (HA) expression in the preceding information. In language, this entails that the difference between HA and LA can be represented by whether, at the point of the relative pronoun ('who'), an integration must be made with a simple (e.g., 'I see the knives of *the cook who* was fired', LA) or a more complex (e.g., 'I see *the teachers of the school* who were fired, HA) expression. Under the assumption that also the mathematical equations are processed left-to-right (as the finding of Scheepers & Sturt, 2014, support), this might lead to structural priming.

As mentioned earlier, the finding by Scheepers and Sturt (2014) that there is differential priming for left-branched versus right-branched mathematical equations does seem to support an incremental account: it is the incremental processing, rather than the hierarchical representational structure in which it results, that determines structural priming.

We suggest that the cross-domain priming findings we report in Chapters 4 and 5 can also be related to the ‘incremental-procedural’ account. As we have mentioned earlier, the cross-domain priming effects we have found are hard to align with a representational account, given the vast differences in the materials that were studied. Whereas it might be conceivable to have an abstract structural representation which is shared for both linguistic and arithmetic syntactic processing, it is rather far-fetched to extend this to the goal-related thematic structure of action descriptions or the pitch cluster elaborations in our experimental pitch sequences. Nevertheless, as has been shown in our studies, the observed cross-domain priming findings cannot be replicated on the basis of sequential order or superficial phrasing, but do seem to be related to the presence of high versus low attachment dependencies. This pattern of findings aligns well with the ‘incremental-procedural’ account, suggesting that cross-domain attachment priming is based on whether, during sequential processing, an integration of a lower or higher complexity must be made.

A tentative account for structural interactions across domains

The question can be asked how the cross-domain structural priming findings we report in the later chapters relate to the ‘resource sharing’ frameworks discussed in the earlier chapters. From a theoretical viewpoint, ‘resource sharing’ models only hypothesize on interactions in structural processing if high demands on structure processing are simultaneously made across domains. Nevertheless, some proposals can be made.

The core concept of the 'incremental-procedural' account for cross-domain structural priming, in our interpretation, can be summarized as follows; when a participant encounters a structurally complex integration (e.g., a high attachment as compared to a low attachment disambiguation) while incrementally processing materials in one domain, this might benefit the processing of structurally complex integrations in subsequent materials in other domains. Of course, this begs the question which mechanisms and resources might support such a facilitation in incremental processing.

Error-based implicit learning. In psycholinguistics, the phenomenon of structural priming has often been linked to error-based implicit learning accounts (Chang, Dell, Bock & Griffin, 2000; Chang, Dell, & Bock, 2006). As we have seen in the introduction, implicit learning is an important concept in studying how we acquire linguistic and non-linguistic competences in early childhood, but implicit learning also plays a strong role throughout adulthood (e.g., Toscano & McMurray, 2010).

The concept of error-based implicit learning is that behaviour at a given time can be influenced by error information from behaviour at a preceding time point. This error information, in the case of linguistic structure processing, can be seen as a structural prediction error (Trueswell, Tanenhaus & Kello, 1993). What error-based implicit learning proposes, is that prediction errors (e.g., a garden path unexpectancy like *'the horse raced past the barn fell'*, but also less strong prediction violations like a dispreferred HA sentence instead of a preferred LA sentence) will form a gradient error signal, which can then update expectations about following materials (Chang et al., 2006).

Error-based implicit learning accounts have often been taken as an explanation for structural priming. When a participant is presented with a certain linguistic structure (e.g., a passive description like *'the burglar is kicked by the policeman'*), this will update expectations about subsequent descriptions, and facilitate the production and comprehension of similar structures. Importantly, an error-based implicit learning account for structural priming would suggest that structural priming is strongest for unexpected structural primes. After all, the more unexpected the structure of the prime is, the larger the gradient of the error signal, and the more the expectation distribution for subsequent processing will be altered (see Bernolet & Hartsuiker, 2010). This concept is known as the ‘inverse preference’ effect: when something is poorly known, it is subject to greater learning. Thus, encountering a less frequent structure will yield a higher error-based learning, leading to a stronger structural priming effect. This is interesting in relation to relative clause attachment priming as well (see Chapter 4), where it is often found that a (less preferred) HA structured prime has a larger priming effect as compared to a (more preferred) LA structured prime.

Proposed Integration of Research Findings. Thus far, we have suggested that the priming findings observed in Chapters 4 and 5 can be interpreted on the basis of an ‘incremental-procedural’ account. What we mean by this is that the found structural priming effects might be based on a priming of the complexity that is encountered when incrementally processing high attachment as compared to low attachment structures across domains. This incremental account for structural priming can then be related to error-based implicit learning theories (Chang et al., 2000, 2006).

But how does the theory of error-based implicit learning relate to the ‘resource sharing’ models that have been suggested in earlier research (SSIRH, Patel, 2003; SWM, Kljajevic, 2010)? As has been discussed in the introduction, both linguistic (‘constraint satisfaction’ theories, Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995; Dependency Locality Theory, Gibson, 1998, 2000) and non-linguistic (e.g., Tonal Pitch Space, Lerdahl, 2001) models for structural processing suggest that the processing of structural complexities is resource-taxing.

In this sense, it is plausible that error-based implicit learning on the basis of structural difficulties occurs through a change in the recruitment of structural processing resources. The domain-generality of our effects might then be explained following the idea of domain-general cognitive resources supporting structural processing across domains (Slevc & Okada, 2015).

In sum, ‘resource sharing’ models (e.g., Kljajevic, 2010) suggest that a shared pool of (working memory, cognitive control, implicit learning) resources support on-line, incremental structural processing across domains. Therefore, such models clearly hypothesize that the processing of structural difficulties will make a demand on a resource pool which also supports the processing of structural difficulties in other domains (hence, interference effects during joint processing as presented in Chapter 2 are explained). However, ‘resource sharing’ models do not hypothesize any interactions beyond on-line processing. Then how do we explain the cross domain priming findings reported in Chapters 4 and 5? For this, we largely agree with an ‘incremental-procedural’ account of attachment priming (Scheepers et al., 2011), according to which structural priming is based on (an error-based implicit learning of, Chang et al., 2000) structural complexity. This way, the finding of attachment priming across domains fits well with ‘resource sharing’ models suggesting that structural complexity processing is based on a domain-general pool of cognitive resources.

IMPLICATIONS

Global versus Local Structure Processing?

We now turn to a segment in the title of this dissertation that we have not yet directly adressed: ‘overlap in *global* and *local* structure processing’. What is meant by this distinction?

In psycholinguistics, it can be argued that structural processing is mainly studied from a perspective of hierarchical representations. As has been previously mentioned, sentential structure can be represented along a hierarchical tree structure (e.g., Chomsky, 1965), on the basis of syntactic rule representations (e.g., Pickering & Branigan, 1998). However,when we are discussing current research, the ‘resource sharing’ accounts for joint processing and the ‘incremental-procedural’ account for structural priming do not assume that cross domain interaction effects are based on global hierarchical representations, but rather model the findings of cross-domain interactions in structure processing through more local, incremental accounts.

Incremental processing in language. It can be noted that the incremental approach to structural processing in the current dissertation stands somewhat in contrast to the study of structural processing (and especially structural priming) in psycholinguistics, which usually refers to global hierarchical representations (e.g., Pickering & Branigan, 1998). Nevertheless, there are some arguments in favour of studying linguistic syntax processing at an incremental level.

A first argument stems from evolutionary adaptivity. Given that language is assumed to involve pre-existing neural mechanisms, it is very plausible (as developed in temporal integration models, Tillmann, 2012) that our capacity to process linguistic structure might rely on an evolutionary older system for accurately processing action events. In contrast to the hierarchical structure which is (at times with great difficulty) explicitly acquired in arithmetics, the structural processing of language (though it can formally be modelled and explicitly taught as a hierarchical structure) is a skill that is largely acquired through the implicit learning of probabilities governing the incremental comprehension of speech.

A second argument can be found on a neurophysiological basis. Several brain regions (e.g., Broca’s area) which have long been pinpointed as neural regions supporting the processing of hierarchical structure in linguistic materials, have also been repeatedly implicated in the processing of non-hierarchical sequential information (Kljajevic, 2010). In fact, several studies from the field of sequential cognition (e.g., Dominey, Hoen, Blanc, & Lelekov-Boissard, 2003) suggest a strong link between hierarchical structure processing in language and sequential processing abilities.

Third, when regarding recursive neural network models approaching linguistic structure processing capacities, several studies (e.g., Saffran, 2002; Chang et al., 2000) have shown that regardless of the assumption of a hierarchical basis in language processing, incremental approaches to modelling linguistic processing have shown much promise. In summary, whereas the role of the sequential structure of language might be somewhat neglected in cognitive science, several trends are converging which address linguistic behaviour through sequential structure. A comprehensive account thereof can be found in a recent paper by Frank, Bod and Christiansen (2012).

Language as a Cognitive Domain

The research presented in our dissertation also touches upon a very interesting question: to what extent can language be regarded as a specific cognitive domain? In relation to what has been said in the introduction of this dissertation, cognitive science largely assumes a modularity of cognitive functions along content domains (Fodor, 1983; Barrett & Kurzban, 2006). In other words, the structural processing of language is largely assumed to be domain-specific. To a certain extent, this is of course rightfully so. The lexical, grammatical and pragmatic regularities governing our capacity for processing language are of course language-specific, and recent neurophysiological data have convincingly shown the existence of language-specific areas in the brain (Fedorenko et al., 2011, 2012).

Nevertheless, as the research that is presented in the current dissertation corroborates, the processing of linguistic information might also call on more domain-general resources, which are limited in terms of attention, working memory, cognitive control, and so on. Whereas the neurophysiological markers of language-specific input and domain-general processing resources (working memory, cognitive control) are spatially distinct, there are several indications that domain-general circuits are involved in language processing (Sharp, Turkheimer, Bose, Scott, & Wise, 2010). In recent studies (Fedorenko & Thompson-Schill, 2014), it has been argued that it would be beneficial for both the understanding of language-specific processing as well as more domain-general cognition to more closely examine how the two relate. Such a request is strongly supported by the results reported in the current dissertation.

Effects of non-linguistic processing on cognitive functions

The research that has been presented in the current dissertation suggests that structural processing across domains (language, music, and math) is supported by a domain-general pool of cognitive resources (e.g., working memory, cognitive control). On the basis of this evidence, it can be expected that structural processing capacities in one domain can boost the resources available for structural processing in another domain, *through domain-general cognitive resources*.

Evidence in favour of cross-domain training effects has already been presented in the introduction of this dissertation. Children have shown enhanced linguistic processing on the basis of musical training (Jentschke & Koelsch, 2009; Anvari, Trainor, Woodside & Levy, 2002), and difficulties in processing linguistic syntax have been related to problems in harmonic processing (Jentschke, Koelsch, Sallat, & Friederici, 2008).

However, following the interpretation of the results reported in the current dissertation, we would hypothesize that such interactions in structural processing across domains are largely based *on general cognitive resources*. In recent years, studies have indeed found a relationship between training of structural processing (e.g., music training) and general cognitive capacities. For instance, a recent school-based longitudinal study has provided evidence that musical training can affect developmental plasticity (Tierney, Krizman & Kraus, 2015). When looking at older individuals, musical training is also associated with neural plasticity (Bidelman & Alain, 2015). When looking at musical expertise, it has recently been shown that adult musicians (as compared to non-musicians) have an enhanced performance on measures of cognitive flexibility and working memory (Zuk, Benjamin, Kenyon & Gaab, 2014).

In line with the ‘resource sharing’ frameworks mentioned earlier, it thus seems that certain domain-general resources (working memory, cognitive control, error monitoring) can indeed be trained across content domains. Musical training might be a valuable tool here, since typically developing children show an awareness of musical structure from around the age of 6-7 years (Schellenberg, 2005). Therefore, from a young age onwards, musical training might be used as a catalyst for the development of domain-general cognitive functions (Schellenberg, 2004).

FUTURE RESEARCH

It must be acknowledged that much of the research provided in this dissertation is based on novel paradigms, and provides primary evidence, which needs to be interpreted with caution until it has further been replicated and elaborated upon. From what has been shown thus far, a few concrete suggestion for further research can be made.

Structural Priming and Action

In Chapter 4 and 5, structural priming effects have been observed on the basis of means-end action descriptions. It might be tempting therefore to draw a link between the structural priming findings that were presented and the domain of action.

Action as a Plausible Domain for Priming. As has been mentioned in the introduction, the syntax which can be observed in the domain of action has often been suggested as an evolutionary basis for structural processing in language and music (Fitch & Martins, 2014). In general, whereas the structural principles of linguistic and musical materials are highly specific, the syntax of action might be regarded as a more transparent framework for studying structural processing. In this ‘action syntax’, subactions can be linked to the main action on the basis of their preparatory nature (Fujita, 2009; Greenfield, 1991). This is similar to the ‘means-end’ descriptions used in the priming studies of this dissertation. Hence, the link between action syntax and linguistic or musical syntax can be easily made by seeing basic actions as discrete elements, which are then made meaningful by linking them around the main action.

On a neurophysiological level, several studies (e.g., Jirak, Menz, Buccino, Borghi & Binkofski, 2010) have reported evidence suggesting that the same neural networks underlying action simulation are also active during the processing of language. For example the responding to manual action verbs has shown to incite activity in the hand regions of the premotor cortex, suggesting that the action descriptions led to an embodiment of those actions (Willems, Hagoort, & Casasanto, 2010; Jirak et al., 2010). Similarly, Hauk, Johnsrude, and Pulvermuller (2004) have shown sensorimotor activations for actions relating to specific verbs (e.g., *‘lick’*, *‘pick’*, *‘kick’*). More specifically to structural processing, Broca’s area has long been seen as a core region in the structural processing of both language and action ,but also other regions, such as the Superior Parietal Lobule (SPL, Heim, Amunts, Hensel, Grande, Huber, Bikonfski & Eickhoff, 2012), have been linked to the sequencing of speech and action. Therefore, it is plausible that the structural overlap of sentences and action sequences shows overlap (Allen et al. 2010; Somerville, Woodward & Needham, 2005; Trabasso, 2005).

From Action Descriptions to Action Sequences. To what extent can we assume that there is a relationship between the action descriptions that were used in the reported cross domain priming studies (Chapters 4 and 5), and the actual visual processing of such action sequences? Allen et al. (2010) have shown that videos of actions could facilitate the processing of linguistic descriptions of action sequences with a similar hierarchical action structure.

More recently, Kaiser (2012) showed that participants were more likely to make causal sentence continuations (i.e., continuing a sentence based on the causal events in that sentence: *'I hit Mary… Mary cries'*) when they first had to repeat two means-end related actions shown by the experimenter, as compared to two separate actions. Therefore, relating the action descriptions used in the reported studies to visual action processing might not be that far-fetched.

Structural Priming and Harmonic Music

Another interesting perspective for future research might be to look whether the joint processing interference effects and especially the structural priming effects can also be replicated when using harmonic melodies instead of experimentally manipulated pitch sequences. Though it is important to disseminate the possible influence of formal musical knowledge on the abovementioned measures, the pitch sequences used in the current dissertation might not be ecologically valid and furthermore, not tap into the large implicit knowledge concerning musical structure that even non-musicians have built up throughout their daily lives. Furthermore, using harmonically composed music has the advantage that musical production (completing a harmonic progression for example) can also be more easily studied.

It is conceivable that structural processing interference found on the basis of our auditory pitch sequences also stretches to harmonically composed music. After all, as mentioned extensively in the introduction, most of the previous research concerning joint structural processing of linguistic and non-linguistic materials has focused on harmonic music (e.g., Slevc et al., 2009). Nevertheless, it might be worthwhile to directly investigate how the cluster manipulations in the auditory pitch sequences used thus far can be related to hierarchical structure processing in harmonically composed music.

LIMITATIONS

As has been mentioned earlier, it is important to acknowledge that the studies reported in this dissertation largely provide primary research (development of pitch sequences, development of recognition measures, first structural attachment priming from auditory sequences and action-related descriptions, and so on). Of course, a further replication and generalization of the found effects is certainly needed.

Another point is that the research that has been reported in the current dissertation is largely based on empirical research questions; ‘Can we find interactions during joint processing tasks on a non-linguistic structural processing measure?’, ‘Can we find effects from structural disambiguation in one domain upon the structural predictions in another domain?, ‘Can we replicate cross-domain attachment priming for pitch sequences and action descriptions?’, and so on. All these questions provide a novel perspective on domain-generality in structural processing, but are mostly directed to investigating if there *is* an interaction, rather than *which* mechanisms support this interaction.

Therefore, it must be acknowledged that the interpretations of our results, as we have reported them in the abovementioned discussion, are suggestive and largely based on other ongoing research. To exemplify what we mean, take the idea that ‘domain-general resources’ might be interpreted along the lines of working memory (Kljajevic, 2010) or cognitive control (Slevc & Okada, 2015). Whereas we can state that the broad scope of our research findings is in line with such general accounts, direct research on working memory involvement (e.g., Fiveash & Pammer, 2012) or cognitive control (e.g., Slevc et al., 2013) has not been replicated in our studies. The same can be said for the ‘incremental-procedural’ account we have adapted for the interpretation of our cross domain structural priming findings: whereas our findings agree with this account, direct tests (e.g., Scheepers & Sturt, 2014) have not been used in the current dissertation.

In sum, we must state that whereas our dissertation was mainly directed towards providing evidence for the *existence* of interactions in structural processing across domains, further research is definitely needed to provide evidence on our suggestive interpretations on what the *cause* of such cross-domain interactions might be.

GENERAL CONCLUSION

The research that has been presented in the current dissertation aims to address the recent debate concerning the extent to which structural processing across content domains (language, music, math, and action) might be supported by domain-general resources (Slevc & Okada, 2015).

Following the development of novel pitch sequences and an off-line structural processing measure, we found interference during the joint structural processing of sentences and pitch sequences, which suggests that structural processing in both domains is supported by a domain-general pool of (working memory and cognitive control) resources.

On the basis of this finding, we investigated to what extent such interactions between the structural processing of linguistic and non-linguistic materials could be found when studying ecologically valid materials. In an EEG study, we found that the event-related potentials (P2, P3, LAN, and P600) which were observed for dispreferred sentential disambiguations could be influenced by structural expectations on the basis of previously disambiguated pitch sequences.

In two subsequent structural priming studies, we found that the completion of syntactically (Scheepers et al., 2011) and thematically (Allen et al., 2010) structured sentence beginnings (Scheepers et al., 2011) could be primed by the attachment structure of preceding linguistic, mathematical and pitch sequence materials. Furthermore, we found that similar cross-domain priming effects could be observed on the perception of implicitly structured pitch sequences. These findings thus strongly argue for broad, domain-general interactions in structural processing even when studying more naturalistic processing of ecologically valid materials.

We tentatively interpret the current findings as evidence in favour of a domain-general pool of cognitive processing resources supporting structural processing across domains (Kljajevic, 2010; Slevc & Okada, 2014). With regards to our cross domain priming findings, we suggest that our results align with an ‘incremental-procedural’ account of attachment priming (see Scheepers & Sturt, 2014) according to which encountering a complexity in the structural processing of materials might (through a process of error-based implicit learning, Chang et al., 2006) influence the resource allocation during the structural processing of subsequent materials. In this way, our cross domain priming findings can be aligned with the idea of structural complexities processing being supported by domain-general cognitive resources (Slevc & Okada, 2015).

At this point, it is important to remark that the results reported in the dissertation should of course be further replicated, and might be generalized to include harmonic processing and action perception as domains of structural processing. Furthermore, the interpretations of the current findings are not fully conclusive, as our studies were mainly guided by the goal of investigating *whether* there was evidence for interaction in structural processing across domains (showing several primary findings), rather than directly comparing alternative accounts in the interpretation of such interactions.

Nevertheless, the research reported in the current dissertation clearly shows that, in relationship to the ongoing discussion on domain-generality of structural processing across domains (Slevc & Okada, 2015), interactions in structural processing across domains can be found when controlling for limitations of previous research (Perruchet & Poulin-Charronnat, 2013), and that those interactions can also be observed in situations that more closely approximate the processing of information from several domains in 'daily life'. These primary findings suggest that domain-general cognitive processing resources support structural processing across domains, which provides several perspectives for theoretical approaches in psycholinguistics as well as other domains of cognition involving structural processing, such as math, music, and action.

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NEDERLANDSTALIGE SAMENVATTING

In de huidige dissertatie wordt onderzoek gepresenteerd omtrent structurele verwerking, wat bondig omschreven kan worden als de capaciteit die we hebben om elementen te combineren op een zodanige manier dat we de relatie tussen deze elementen kunnen achterhalen. Als voorbeeld: in onze taal hebben we de (uniek menselijke) capaciteit om bepaalde woorden (bv. ‘hond’, ‘bijten’, ‘slang’) te combineren in zinnen, die meteen ook iets weergeven over de relatie tussen die woorden (bv. *‘de hond bijt de slang’* is niet hetzelfde als *‘de hond wordt gebeten door de slang’*). Uit dit voorbeeld blijkt meteen ook hoe structurele verwerking van groot belang is om taal te begrijpen.

Maar taal is niet het enige domein waar structurele verwerking van belang is. Denk bijvoorbeeld aan wat er gebeurt bij het beluisteren van muziek. Zelfs personen die geen muzikale opleiding hebben gevolgd, zullen al snel het verschil herkennen tussen een melodie of een willekeurige opeenvolging van tonen. Meer zelfs, zij zullen vrij nauwkeurig kunnen aangeven wanneer een muzikant een verkeerd akkoord speelt. Dergelijke voorbeelden tonen aan dat we ook in muziek steeds tonen beluisteren in relatie met wat we eerder gehoord hebben. Een ander voorbeeld vinden we in wiskunde. Een vraagstuk zoals *‘3+(2*(2+5))’* zal enkel correct opgelost kunnen worden indien de regels waarmee de verscheidene cijfers en tekens gecombineerd zijn, gerespecteerd worden.

Hoewel structurele verwerking voornamelijk bestudeerd wordt als een specifieke functie binnen verscheidene domeinen (taalsyntax, muzikale harmonie, enzovoort), kan er opgemerkt worden dat dezelfde vragen en thema’s terugkomen overheen domeinen: Hoe worden structurele verwerkingsregels aangeleerd, en hoe worden ze toegepast op nieuwe informatie? De antwoorden die ontwikkeld zijn op dergelijke vragen, zijn ook sterk gelijkend overheen domeinen. Impliciet leren wordt gezien als een belangrijke manier van regelverwerving in zowel taal als muziek (Dienes, 2011; Perruchet, 2008), en de manieren waarop deze regels toegepast worden op binnenkomende informatie (structurele integratie, Gibson, 1998; Lerdahl, 2001; structurele verwachtingen, Levy, 2008; Byros, 2009) zijn ook erg gelijkend over verscheidene domeinen heen. Dergelijke gelijkenissen hebben dan ook geleid tot een ontwikkeling van modellen (bv. ‘Syntactic Working Memory’ van Kljajevic, 2010) die veronderstellen dat structurele verwerking overlap vertoont overheen domeinen.

Hoe kan deze overlap overheen domeinen gemodelleerd worden? Het is natuurlijk zo dat de regels die structurele verwerking bepalen specifiek zijn voor een bepaald domein (bv. syntaxregels in taal versus harmonie in muziek). Tot op een bepaald vlak zal er dus ook steeds een onderscheid zijn in structurele verwerking tussen domeinen (Allosa & Castelli, 2009). Niettemin kan worden verondersteld dat de cognitieve hulpbronnen (‘resources’) waarop beroep gedaan wordt voor structurele verwerking, gedeeld kunnen zijn tussen domeinen (Patel, 2008; Slevc & Okada, 2015). Indien dezelfde cognitieve hulpbronnen worden aangesproken bij structurele verwerking van talige maar ook niet-talige materialen, kan dit de grote overlap verklaren in de bevindingen van studies rond structurele verwerking in verschillende domeinen verklaren (Cross, 2011; Brandt, Gebrian & Slevc, 2012).

Op welke manier kunnen we nagaan of er inderdaad domein-overschrijdende cognitieve hulpbronnen zijn voor structurele verwerking? Een veel gebruikte manier is om experimentele paradigmata te ontwikkelen waarbij participanten tegelijkertijd structurele moeilijkheden moeten verwerken in zowel talige als niet-talige materialen. Indien er inderdaad gedeelde cognitieve hulpbronnen aangesproken worden tijdens structurele verwerking, zou een veeleisende structurele verwerking in het ene domein namelijk moeten interfereren met een gelijktijdige structurele verwerking in het andere domein. Dergelijke bevindingen van interferentie in het gelijktijdig verwerken van structurele moeilijkheden overheen domeinen zijn inderdaad herhaaldelijk gerapporteerd (Slevc, Rosenberg & Patel, 2009; Fedorenko, Patel, Casasanto, Winawer, & Gibson, 2009). Slevc et al. (2009) vonden bijvoorbeeld dat de leestijd van een structurele moeilijkheid (aan de hand van intuinzinnen zoals ‘ik sloeg de man met de stok *gade*’, waarbij het woord *‘gade’* een herstructurering van de zin inleidt) vergroot werd als participanten tegelijkertijd ook een harmonisch incongruent akkoord in de begeleidende melodie moesten verwerken. Dit werd niet gevonden voor de leestijd van semantisch onverwachte woorden (bv. ‘de postbode fietst snel weg van de agressieve *varkens*’, waarbij men een ander woord zoals ‘honden’ had verwacht). Het idee dat er interferentie is tussen harmonische verwerking van de melodie en de structurele (maar niet semantische) verwerking van de zin wordt dan gezien als evidentie voor de betrokkenheid van domein-overschrijdende cognitieve hulpbronnen bij structurele verwerking.

Niettemin zijn er enkele beperkingen aan dergelijke paradigmata. Ten eerste werden interferentie-effecten tot nu toe voornamelijk gemeten op basis van algemene taalverwerking (zoals de leestijden bij Slevc et al., 2009), waarbij via experimentele contrasten (bv. het contrasteren van structurele en semantische onverwachtheden) structurele verwerking geïsoleerd werd. Dergelijke experimentele contrasten werden echter in recent onderzoek sterk bekritiseerd (Perruchet & Poulin-Charronnat, 2013). Ten tweede is het zo dat het vinden van interferentie-effecten via het gelijktijdig aanbieden van structurele moeilijkheden overheen domeinen weliswaar bewijs aanbrengt voor ‘resource sharing’ modellen, maar verder niet echt ecologisch valide is. In ons dagelijks leven komen we zelden structurele moeilijkheden tegen in (vooraf opgenomen of opgeschreven) taal en muziek. Bijvoorbeeld, de intuinzinnen bij Slevc et al. (2009) zijn net intuinzinnen omdat ze zo weinig voorkomen in ons taalgebruik, en harmonisch onverwachte akkoorden zouden vals klinken in gecomponeerde muziek. Het idee dat deze onverwachtheden gelijktijdig aangeboden worden, is al zeker niet erg ecologisch valide. De vraag kan dus gesteld worden in hoeverre dergelijk interferentie-onderzoek ons iets te vertellen heeft over onze dagdagelijkse structurele verwerking.

In de huidige dissertatie werden deze twee vragen opgenomen. In relatie tot de eerste beperking (problemen met het gebruik van experimentele contrasten) werd in dit proefschrift een herkenningstaak ontwikkeld die (zonder gebruik van experimentele contrasten) een maat voor structurele verwerking van toonsequensen kan bieden. Aan de hand van dergelijke maat hebben we de recente kritiek (Perruchet & Poulin-Charronnat, 2013) op eerder interferentie-onderzoek direct aangekaart. In relatie tot de tweede beperking (zijnde dat interferentie-onderzoek relateert weinig relateert aan dagelijkse structuurverwerking) hebben we in een reeks van studies onderzocht in welke mate interacties tussen de structurele verwerking van talige en niet-talige materialen gevonden kunnen worden wanneer er gewerkt wordt met een niet-gelijktijdige aanbieding van meer ecologisch valide materialen. Hieronder rapporteren we kort onze bevindingen.

INTERFERENTIE-ONDERZOEK OP NIET-TALIGE STRUCTUURVERWERKING

Zoals in Hoofdstuk 1 beschreven wordt, is er in recente jaren kritiek gekomen op de contrastcondities (Perruchet & Poulin-Charronnat, 2013) die in eerder interferentie-onderzoek (Slevc et al., 2009) gebruikt werden om structuurverwerking in taal te meten. Bovendien kan de vraag gesteld worden in welke mate interferentie ook gevonden kan worden wanneer gekeken wordt naar talige invloed op niet-talige structuurverwerking. Om een antwoord te bieden op dergelijke kritiek, hebben we in de huidige dissertatie toonsequensen ontwikkeld met een experimenteel gemanipuleerde structuur. Vervolgens hebben we een herkenningsmaat ontwikkeld, gebaseerd op Tan, Aiello en Bever (1981), die aangeeft in welke mate de structurele grenzen in een toonsequens verwerkt worden. Op deze manier konden we dus, zonder gebruik van contrastcondities, rechtstreeks de effecten van structurele moeilijkheden in taal op de gelijktijdige verwerking van structurele grenzen in onze toonsequensen meten.

Dit werd concreet uitgevoerd in de studie die gerapporteerd wordt in Hoofdstuk 2. In deze studie werden participanten gerekruteerd in een dubbeltaakparadigma waarin zij zinnen dienden te lezen terwijl onze experimenteel gemanipuleerde toonsequensen aangeboden werden. Uit de metingen van de daaropvolgende toonherkenningstaak bleek dat het aanbieden van onverwachtheden in de zinnen de verwerking van structurele grenzen in de toonsequens verlaagde. Deze interferentie vond echter enkel plaats wanneer de onverwachtheden in de zin een structurele moeilijkheid inhielden, en wanneer zij gelijktijdig met de structurele grens in de toonsequensen aangeboden werden. Met andere woorden, deze studie bevestigt eerder interferentie-onderzoek (Slevc et al., 2009) aan de hand van een specifieke maat voor niet-talige structuurverwerking. Daarbij biedt zij een direct antwoord op recente kritieken (Perruchet & Poulin-Charronnat, 2013), alsook sterke evidentie voor het idee van een gedeelde resources voor structurele verwerking overheen domeinen.

VAN INTERFERENTIE NAAR STRUCTURELE PREDICTIE

Zoals eerder gezegd had de huidige dissertatie ook als doel te onderzoeken in welke mate evidentie voor interacties in de structurele verwerking van materialen overheen domeinen ook gevonden kon worden buiten interferentie-onderzoek. Het is namelijk zo dat interferentie-onderzoek (gelijktijdige aanbieding van structurele onverwachtheden overheen domeinen) weinig beantwoordt aan hoe structurele verwerking plaatsvindt in het dagelijkse leven. Vanuit recent psycholinguïstisch onderzoek (e.g., Scheepers & Sturt, 2014) wordt echter gesuggereerd dat interacties in structurele verwerking overheen domeinen ook in meer naturalistische settings gevonden kunnen worden. Meer specifiek betreft het hier de priming van structurele aanhechting: het idee dat, na verwerken van materialen met een bepaalde syntactische aanhechting (bv. ‘ Ik zie *de lichten* van de kamer *die blauw zijn*’ tegenover ‘Ik zie de lichten van *de kamer die blauw is*’), een dergelijke aanhechting ook in latere verwerking geprefereerd wordt. Interessant hier is dat dergelijke aanhechtingsstructuren ook ontwikkeld kunnen worden in niet-talige materialen. Bijvoorbeeld, in toonsequensen kunnen er ook segmenten zijn die (harmonische) uitbreidingen zijn van een eerder begonnen segment. In de huidige dissertatie werd dan ook uitvoerig onderzocht in welke mate interactie tussen de structurele verwerking van talige en niet-talige materialen gevonden kon worden op basis van deze naturalistische aanhechtingsstructuren, eerder dan op basis van de structurele onverwachtheden die men in interferentie-onderzoek vindt.

In Hoofdstuk 3 werden mogelijke interacties tussen structurele verwerking van talige en niet-talige materialen onderzocht aan de hand van zinnen en toonsequensen die een hoge of lage aanhechtingsstructuur hadden. In een EEG-experiment lazen participanten betrekkelijke bijzinstructuren terwijl ze luisterden naar toonsequensen. Hierbij hadden de zinnen echter een erg late structurele desambiguatie, nadat de aanhechtingsstructuur van de toonsequens reeds gedesambigueerd was. Met andere woorden, in tegenstelling tot eerder interferentie-onderzoek (zie Hoofdstuk 2) was er hier geen gelijktijdige aanbieding van structurele moeilijkheden. De manipulatie in de EEG-studie bestond er in dat de aanhechtingsstructuur van beide materialen gelijk gehouden werd in het overgrote deel van de aanbiedingen. In 80% van de aanbiedingen volgde de structurele desambiguatie van de zin de aanhechtingsstructuur van de eerder gedesambigueerde toonsequens. Op deze manier (ook al waren beide materialen onafhankelijk en was er geen interferentie omtrent hulpbronnen) konden participanten structurele voorspellingen maken voor het ene domein op basis van een eerdere structurele verwerking van materialen in het andere domein. De resultaten van de EEG studie toonden aan dat ERP-componenten gerelateerd aan het verwerken van een niet-geprefereerde aanhechtingsstructuur (P3, LAN, P600) duidelijk beïnvloed werden door de mate waarin dergelijke desambiguatie voorspeld kon worden op basis van de eerder gedesambigueerde toonsequens. Met andere woorden, de EEG-studie die gerapporteerd wordt in Hoofdstuk 3 geeft evidentie voor het idee dat zelfs tijdens het sequentieel structureel verwerken van naturalistische materialen, interacties gevonden kunnen worden overheen domeinen.

Op basis van de resultaten in Hoofdstuk 3 hebben we ons verder gericht op het bestuderen van recente bevindingen (Scheepers, Sturt, Martin, Myachykov, Teevan, & Viskupova, 2011; Scheepers & Sturt, 2014) omtrent aanhechtingspriming over domeinen heen. Hoofdstuk 4 rapporteert een studie waarbij we toonsequensen presenteerden als een structurele prime voor een zinsaanvultaak, gebaseerd op betrekkelijke bijzinstructuren (bv. *'Ik zie de lichten van de kamer die…'*). De participanten vertoonden een tendens om de betrekkelijke bijzinnen aan te vullen met een aanhechtingsstructuur die analoog was aan die van de eerder verwerkte toonsequensen. Een dergelijk structureel primingeffect werd echter niet gevonden voor kleursequensen, waarbij de relatie niet structureel van aard was. Deze studie bevestigde dat het primingeffect dus gebaseerd is op de aanhechtingsstructuur van de toonsequens. In een daaropvolgend replicatie-experiment werd dergelijke aanhechtingspriming niet enkel gevonden van toonsequensen naar het aanvullen van betrekkelijke bijzinstructuren, maar ook van gelijkaardig gestructureerde wiskundevragen (bv. *'3+(2*(2+5))'* vormt een lage aanhechting, en *'3+(2*2)+5'* vormt een hoge aanhechting). Ook doelgerichte actiebeschrijvingen (bv. 'ik neem de telefoon, neem de schaar, en bel' vormt een hoge aanhechting en 'ik neem de schaar, neem de telefoon en bel' vormt een lage aanhechting) vertoonden priming op het aanvullen van betrekkelijke bijzinstructuren (bv. *'Ik zie de lichten van de kamer die….'*). Gelijkaardige primingeffecten werden ook gevonden wanneer gekeken werd naar de invloeden van bovenstaande primingmaterialen op het aanvullen van actiebeschrijvingen. Deze reeks experimenten toont duidelijk aan dat de productie van talige informatie, zijnde via syntactisch of thematisch gestructureerde zinnen, beïnvloed wordt door eerdere structurele verwerking overheen verscheidene domeinen.

In Hoofdstuk 5 worden de onderliggende mechanismen van de aanhechtingspriming uit Hoofdstuk 4 verder besproken. Hoewel Hoofdstuk 4 duidelijke primingeffecten toont tussen domeinen, is het belangrijk dat een dergelijke aanhechtingspriming tot nu toe enkel gevonden is in onderzoek naar de verwerking van gestructureerde, geschreven materialen. Daarom werd de vraag gesteld in welke mate dergelijke aanhechtingspriming gevonden kan worden wanneer gekeken wordt naar niet-talige, impliciet gestructureerde informatie. Gebaseerd op Hoofdstuk 4 onderzochten we of de structurele verwerking van toonsequensen onder de invloed staat van eerdere structuurverwerking. Deze studie toonde aan dat de aanhechtingsstructuur van eerder aangeboden toonsequensen, betrekkelijke bijzinstructuren en actiebeschrijvingen duidelijk invloed had op de daaropvolgende structurele integratie van toonsequensen. Dit biedt niet enkel een replicatie van de cross-domein priming op een nieuw domein, maar bevestigt verder dat deze vorm van structurele priming gedreven kan worden door impliciete mechanismen van integrationele structuurverwerking.

DISCUSSIE

De interferentie-studie die in Hoofdstuk 2 besproken wordt biedt evidentie voor ‘resource sharing’ modellen (Kljajevic, 2010), in zoverre dat zij aangeeft dat structurele verwerking van zowel talige en niet-talige materialen gebaseerd is op overlappende cognitieve hulpbronnen. Gezien de materialen die gebruikt werden voor deze studie (experimenteel gemanipuleerde toonsequensen), sluit deze studie wel eerder aan bij conceptualisaties van deze hulpbronnen als algemene cognitieve hulpbronnen (bv. werkgeheugen, Kljajevic, 2010; cognitieve controle, Slevc, Reitman & Okada, 2013), dan als syntax-specifieke resources (Patel, 2003).

De interacties die gevonden worden in de sequentiële structurele verwerking van materialen overheen domeinen in Hoofdstuk 3, 4 en 5, suggereren een overlap in structurele verwerking buiten wat door de huidige ‘resource sharing’ modellen voorspeld wordt. Zij tonen namelijk aan dat zelfs zonder een gelijktijdige uitputting van domein-overschrijdende cognitieve resources ook interacties tussen structuurverwerking overheen domeinen gevonden kunnen worden. Dergelijke interacties in sequentiële structurele verwerking van talige en niet-talige informatie kunnen we verklaren binnen een ‘incrementeel-procedurele’ uitleg voor structurele primingeffecten (zie Scheepers et al., 2011). Volgens deze verklaring wordt de sequentiële invloed van structuurverwerking overheen domeinen bepaald door priming van complexiteit in incrementele verwerking, hetgeen gerelateerd kan worden aan modellen die structurele priming verklaren via impliciet leren (bv. Chang, Dell, Bock, & Griffin, 2000). Volgens deze modellen zouden we kunnen zeggen dat het verwerken van structureel complexe elementen (hetgeen volgens ‘resource sharing’ modellen gerelateerd is aan een rekrutering van domein-overschrijdende cognitieve hulpbronnen) een opeenvolgende verwerking van een gelijkaardige structurele complexiteit faciliteert. Op deze manier kan men de interacties in de sequentiële structurele verwerking overheen domeinen dus ook kaderen binnen de ‘resource sharing’ modellen.

In een kritische bespreking van de resultaten die gerapporteerd worden in de huidige dissertatie, is het belangrijk op te merken dat de bevindingen die voorgesteld worden voornamelijk primaire bevindingen zijn, die verder gerepliceerd en gegeneraliseerd dienen te worden. Een uitbreiding naar visuele actieverwerking en harmonische melodieverwerking biedt interessante mogelijkheden voor verder onderzoek. Verder kan de opmerking gemaakt worden dat de bevindingen van de studies die gerapporteerd zijn, vooral gericht zijn op de bevinding dat er interactie in structuurverwerking overheen domeinen *aanwezig* is. De interpretaties van dergelijke interacties dienen echter verder onderbouwd te worden door verder gericht onderzoek (b.v., Fiveash & Pammer, 2012).

In conclusie kunnen we stellen dat het onderzoek dat gerapporteerd wordt in de huidige dissertatie duidelijk aangeeft dat interacties in structurele verwerking overheen talige en niet-talige materialen gevonden kunnen worden, niet alleen wanneer men controleert voor beperkingen in eerder onderzoek (zie Perruchet & Poulin-Charronnat, 2013), maar verder ook wanneer men onderzoek doet naar meer naturalistische situaties (zie structurele priming, Scheepers & Sturt, 2014). Dergelijke bevindingen suggereren dus dat structurele verwerking overheen domeinen inderdaad ondersteund wordt door algemene cognitieve hulpbronnen (Slevc & Okada, 2015), wat interessante perspectieven biedt voor zowel de theoretische studie van structuurverwerking, als voor meer toegepast onderzoek naar structuurverwerking in dagelijkse settings.

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APPENDIX 1: STRUCTURAL PHRASING STUDY

Preface

The study reported in Chapter 4 provides evidence in favour of cross-domain priming across an array of experiments. Experiment 1a and Experiment 2 show that the attachment choice in the completion of relative clause sentences (e.g., *'I see the lights of the room that…'*) and in the completion of means-end action descriptions (e.g., *'I take my keys, start up the computer, and….'*) could be primed by processing the attachment structure of preceding sentences, math equations, and even pitch sequences.

As mentioned in Chapter 4, a control experiment (Experiment 1b) found that such attachment priming effects could not be replicated on the basis of sequential order. More specifically, the order of colour sequences (e.g., *'red'*-*'blue'*-*'blue'* versus *'red'*-*'blue'*-*'red'*) could not prime the attachment of following relative clause completions. However, the remark can be made that these colour sequences were not part of the original materials on the basis of which cross-domain priming effects were found.

Therefore, we ran a second control experiment, in which we made order manipulations on the pitch sequence materials which were used in the study reported in Chapter 4. Specifically, we addressed the question how the presentation of 'ABA' sequences (high attachment of the last segment to the initial pitch cluster) and 'ABB' sequences(low attachment of the last segment to the second pitch cluster), which were used in Chapter 4, would compare to the presentation of an 'ABC' pitch sequence, in which a secondary pitch cluster shift was present, which did however not attach to any of the preceding pitch clusters. Should we find a similar priming for 'ABA' and 'ABC' pitch sequences to evoke more high attachment linguistic completions, this would suggest that it is the order of structural boundaries, rather than the dependency they entail, which causes the previously reported cross-domain priming effects.

Method

Participants.

We recruited 28 participants from the Ghent University student pool. All participants were native speakers of Dutch, and participated in exchange for course credits.

Materials.

Sentences. 95 incomplete relative clause sentences were made, 5 for the practice trials and 90 for the experimental trials. In similarity to the materials presented in Chapter 4, 60 sentence beginnings were ambiguous (e.g., *'I see the lights of the room that….'*), and could thus be completed with either a high attachment (HA) or low attachment (LA) relative clause. The remaining 30 sentence beginnings were unambiguous (e.g., *'I see the knives of the cook who….'*). Unambiguous sentences were removed for the analysis, but were introduced to force participants to switch between attachment structures.

Pitch sequences. Three types of pitch sequences were constructed, in similarity to the materials used in Chapter 4. Each pitch sequence consisted out of nine sequentially provided tones[7]. To manipulate the structure of the pitch sequences, three pitch clusters were selected ('A B E', 'C F G', and 'Ab Db Eb') exactly as was done in Chapter 4.

For the high dependency structured pitch sequences, a cluster shift would occur between the third and the fourth tone. Between the sixth and the seventh tone, a second cluster shift would lead back to the original pitch cluster. This created an 'ABA'-structured pitch sequence, containing a high

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[7] It is important to notice that whereas the pitch sequences reported by Van de Cavey & Hartsuiker (2016) consisted out of 8 tones, our pitch sequences consist out of 9 tone sequences. The reason for this is that for 'ABC'-sequences, the last (independent) segment would otherwise consist out of two tones, which a preliminary study found to cause processing problems.

dependency (Chapter 4). For the low dependency structured pitch sequences, a cluster shift would occur between the third and the fourth tone, but not between the sixth and seventh tone. This created an ‘ABB’-structured pitch sequence, in line with a low dependency structure (Chapter 4).

In the current experiment, we also created ‘ABC’-structured pitch sequences. For these pitch sequences, a cluster shift would occur between the third and the fourth tone, and between the sixth and the seventh tone. However, the second cluster shift would not lead back to the initial pitch cluster, but to the third pitch cluster. Therefore, even though these ‘ABC’-structured pitch sequences have the same order of pitch cluster boundaries as the ‘ABA’-structured pitch sequences, they do not contain a high dependency structure.

Pitch Sequence Recognition Task.

To determine whether pitch cluster processing occurred as expected, the recognition task used in Chapter 4 was also used in this experiment. 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).

Procedure.

The procedure was similar to what has been reported in Experiment 1a of Chapter 4. Participants performed 90 trials (fully randomized), with each trial consisting of a pitch recognition task and a sentence completion task. For the first task, participants listened to 9-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 colour 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 analysed. But 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.

Design. In 60 of the 90 sentences, the sentence beginnings were ambiguous so that both a HA or LA relative clause structure would be a valid completion. The other 30 sentence beginnings were fillers, in which the sentence beginning was unambiguous (15 HA, 15 LA) so as to force all participants to use both HA and LA structures as completions. The pitch sequences either had an ‘ABA’, ‘ABB’ or ‘ABC’ structure. 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.

Analyses. The same analyses as reported in Chapter 4 were applied to the dataset. 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. Unfortunately, due to a coding error, we had to remove one sentence (sentence 5) from the analysis.

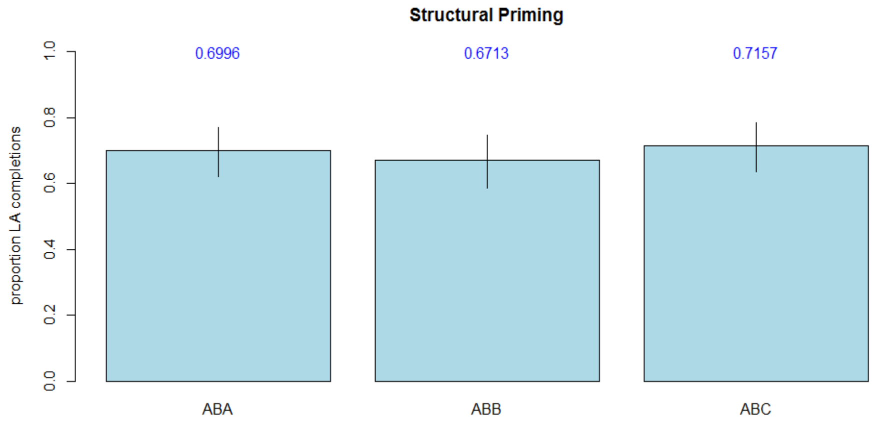
For the probe recognition performance, the independent variables ‘prime structure’ (i.e., HA or LA structures pitch sequences), ‘response’ (i.e., the structure of the sentence completion, HA or LA), and ‘probe’ (i.e., the kind of recognition probe: ‘within’, ‘between’, or ‘foil’) were introduced to the 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 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., 'ABA', 'ABB' or 'ABC' structured pitch sequences), 'correct' (i.e. the performance on the recognition task), and 'probe' (i.e., the kind of recognition probe: 'within', 'between', or '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 3.2.3), using the lme4 package (version lme4_1.1-7). Also for these analyses, the data files and the corresponding R scripts can be found on http://opensciencefraemwork.org/profile/v49bp.

Results

For the pitch recognition task, we found that 'between probes' were recognized correctly in 67% of trials, that 'within probes' were recognized correctly in 64% of trials, and that 'foil probes' were recognized correctly in 73% of trials. It is interesting to see that there is a marginally significant interaction between the 'within probe' advantage and the structure of the pitch sequences (B = 0.348, z = 1.698, Pr (>|z|) = .091). Whereas there was a 'within probe' advantage for the 'ABB'-structured primes of -3%, there was a 'within probe' disadvantage for the 'ABA'-structured primes of -8% and for the 'ABC'-structured primes of -3%. In other words, the results of the pitch recognition task suggest a much poorer structural processing of the 'ABA' and 'ABC' melodies, and bad processing overall.

For the sentence comprehension task, we found no significant differences in relative clause attachment dependent on our structure of the preceding pitch sequences. The proportion of LA completions was 70% after 'ABA'-structured pitch sequences, 67% after 'ABB'-structured pitch sequences, and 72% after 'ABC'-structured pitch sequences. In other words, no structural priming occurred.



Discussion

To address the concern that the color sequence materials used in the control experiment of Chapter 4 did not directly relate to the materials on which structural priming was found, we developed a second control experiment, in which we investigated to what extent the cross-domain structural priming effects for pitch sequences (Experiment 1a in Chapter 4) could be replicated on the basis of order manipulations, rather than attachment manipulations, in our pitch sequences. Our results revealed that the inclusion of pitch sequences which did not contain a dependency structure, removed all structural parsing and structural priming effects, suggesting that the structural processing of our pitch sequences (and priming effects thereof) is largely dependent on the dependency relation they contain.

APPENDIX 2: JOINT PROCESSING MATERIALS

All sentences used in the study which is reported in Chapter 2 can be found below. There are control sentences (CONTROL) which contain a passive-voiced complement clause, structural garden path sentences (GP) which contain a less frequently occurring structural disambiguation, either early or late, and 'out-of-context' sentences (OOC) which contain a word category order early or late in the sentence. Finally, there were also four practice materials (PRACTICE), used to explain the experiment. Words that are joined with an underscore (e.g., 'de_man') were presented in the same sentence segment, so that all sentences could be provided in 8 sequential segments.

Zeg de_arts dat zijn_zoon ontvangen wordt in de_hal	CONTROL
Zeg de_juffrouw dat de_klas ontruimd is voor de_schoonmaak	CONTROL
Vraag de_man of de_doos gevonden werd door zijn_zoon	CONTROL
Vraag de_man of zijn_vrouw onderzocht werd door de_politie	CONTROL
Zeg de_architect dat het_koppel geweigerd werd voor een_lening	CONTROL
Zeg de_non dat de_bisschop opgehouden wordt in de_file	CONTROL
Vraag de_leraar of de_leerling geslaagd is voor zijn_vak	CONTROL
Vraag de_vrouw of haar_zoon vastgehouden wordt door de_boef	CONTROL
Zeg de_pater dat het_beeld schoongemaakt wordt door de_kuisvrouw	CONTROL
Zeg de_vader dat zijn_zoon opgenomen is in het_ziekenhuis	CONTROL
Vraag het_kind of het_speelgoed gekocht werd door zijn_moeder	CONTROL
Vraag de_ambassadeur of zijn_secretaresse aangekomen is in het_hotel	CONTROL
Zeg de_lasser dat het_wiel verbogen is door de_hitte	CONTROL
Zeg de_kok dat het_vlees geleverd is door de_slager	CONTROL
Vraag de_bediende of de_kassa gesloten wordt tijdens de_dienst	CONTROL
Vraag de_klant of de_tafel afgeruimd werd door de_ober	CONTROL
Zeg de_kassier dat het_geld afgehaald wordt door de_agent	CONTROL
Zeg de_juffrouw dat de_klas opgeruimd is door de_kinderen	CONTROL
Vraag de_dokter of het_kind onderzocht wordt op mazelen	CONTROL
Vraag de_timmerman of de_nagels gevonden werden in de_doos	CONTROL

Zeg de_pastoor dat de_kerk vernield wordt door vandalen	CONTROL
Zeg de_leider dat de_kinderen afgehaald worden door hun_ouders	CONTROL
Vraag de_secretaris of de_documenten ondertekend werden door de_werknemers	CONTROL
Vraag de_brandweerman of de_katten gered werden met de_ladder	CONTROL
Zeg de_ridder dat het_kasteel bestormd wordt door de_vijand	CONTROL
Zeg de_luitenant dat de_soldaten gedood worden door de_tank	CONTROL
Vraag de_matroos of het_schip gedoopt wordt door de_kapitein	CONTROL
Vraag de_architect of het_huis ontworpen werd door zijn_assistent	CONTROL
Zeg de_wachter dat de_dieven ontmaskerd werden door een_toerist	CONTROL
Zeg de_klant dat het_restaurant geopend wordt door de_burgemeester	CONTROL
Vraag de_non of het_klooster onderhouden wordt door een_kuisvrouw	CONTROL
Vraag de_vrouw of haar_man onderzocht werd door de_hartchirurg	CONTROL
Zeg de_ouders dat de_leraar ontslagen werd door de_directeur	CONTROL
Zeg de_minister dat zijn_invloed onderschat werd door de_koning	CONTROL
Vraag de_advocaat of de_beklaagde verzocht werd om op_te_staan	CONTROL
Vraag de_kolonel of de_soldaten teruggekeerd zijn van het_slagveld	CONTROL
Zeg de_leraar dat de_student bezocht werd door zijn_ouders	CONTROL
Zeg de_toerist dat de_weg omgeleid wordt wegens een_ongeval	CONTROL
Vraag de_bakker of de_broden afgehaald werden door de_assistent	CONTROL
Vraag de_schrijver of zijn_boeken geschreven worden voor kinderen	CONTROL
Zeg de_kleermaker dat de_stoffen gemaakt werden door handwevers	CONTROL
Zeg de_slager dat zijn_vlees afgekeurd is door de_voedselinspectie	CONTROL
Vraag de_schilder of de_kunstwerken verkocht worden door de_manager	CONTROL
Vraag de_leerling of de_examens afgenomen worden door de_leraar	CONTROL
Zeg de_agent dat de_auto geraakt is door de_tram	CONTROL
Zeg de_man dat de_tafel gekocht is door een_buitenlander	CONTROL
Vraag de_matroos of het_schip gezonken is door de_storm	CONTROL
Vraag de_chirurg of de_patiënt gestorven is door het_ongeval	CONTROL
Zeg de_agent te_verwittigen dat de_overvaller gisteren een_inbraak pleegde	GP early
Zeg de_leraar te_informeren dat de_studenten de_klas hebben versierd	GP early

Vraag de_secretaris te_ontslaan zodat het_personeel terug begint te_werken	GP early
Vraag de_installateur te_bellen om de_studenten te_helpen met de_computers	GP early
Zeg de_brandweer te_bellen indien de_bijen de_kinderen bang maken	GP early
Zeg de_schijver te_feliciteren die het_boek aan de_kinderen voorstelde	GP early
Vraag de_klant te_wachten tot de_ober de_bestelling heeft genoteerd	GP early
Vraag de_dokter te_roepen die de_medicijnen aan het_kind voorschreef	GP early
Zeg de_assistent te_melden dat zijn_baas de_documenten heeft ontvangen	GP early
Zeg de_chauffeur te_waarschuwen dat de_minister naar het_congres gaat	GP early
Vraag de_soldaat te_beschrijven die door de_aanslag gestorven is	GP early
Vraag de_ouders te_melden dat de_kinderen de_schade veroorzaakt hebben	GP early
Zeg de_chirurg dat de_patiënt onderzocht waar de_operatie plaatsvind	GP late
Zeg de_bode dat zijn_baas verzocht snel de_dossiers te_bekijken	GP late
Vraag de_agent of de_boef onderschept welke berichten er_zijn	GP late
Vraag de_agent of de_dader onderschat welke_stappen ondernomen worden	GP late
Zeg de_trainer dat zijn_voetballers verkozen om in_de_bus te_blijven	GP late
Zeg de_ouders dat hun_aanwezigheid vereist dat men nederig_is	GP late
Vraag de_criticus of het_artikel overschat hoeveel luipaarden er_zijn	GP late
Vraag de_ouders of de_kinderen vergeven wat die_dag gebeurd_is	GP late
Zeg de_rechter dat de_kinderen vergeten welke gevolgen er_zijn	GP late
Zeg de_gids dat de_indianen bekeken welke_kleren de_toeristen droegen	GP late
Vraag de_presentator of de_verslagen beschreven welke risico's er_waren	GP late
Vraag de_directeur of de_leerling verwacht dat zijn_resultaten beter_zijn	GP late
Zeg de_vrouw rest haar_zoon onderzocht wordt in het_ziekenhuis	OOC early
Zeg de_directeur deur de_juffrouw vervangen wordt tijdens de_zwangerschap	OOC early
Vraag de_agent kop de_overvaller gearresteerd werd in de_bank	OOC early
Vraag de_priester stel de_kerk bezocht werd door toeristen	OOC early

Zeg de_ouders zaak de_kinderen verwacht worden aan de_schoolpoort	OOC early
Zeg de_directeur avond de_documenten opgestuurd werden naar de_firma	OOC early
Vraag de_man vent het_geschenk afgegeven werd aan zijn_vrouw	OOC early
Vraag de_bakker dollar de_broden gebakken werden in de_oven	OOC early
Zeg de_auteur gezicht het_artikel gepubliceerd is in de_krant	OOC early
Zeg de_piloot nacht het_vliegtuig geraakt is door een_raket	OOC early
Vraag de_officier hart de_soldaat gedood is door de_vijand	OOC early
Vraag de_brandweer klootzak het_vuur gedoofd werd door de_regen	OOC early
Zeg de_leraar dat de_klas opgeruimd stuk door de_kinderen	OOC late
Zeg de_jongen dat het_speelgoed gegeven week door zijn_tante	OOC late
Vraag de_agent of de_vrouw onderzocht kop in het_bureau	OOC late
Vraag de_directeur of de_dossiers opgehaald plek door de_secretaris	OOC late
Zeg de_dokter dat het_meisje gevallen vrij op de_speelplaats	OOC late
Zeg de_leraar dat de_taken ingediend agent door de_leerlingen	OOC late
Vraag de_arts of de_patiënt geopereerd nummer in het_ziekenhuis	OOC late
Vraag de_verkoper of de_aankopen aangerekend hand aan de_kassa	OOC late
Zeg de_bediende dat de_dossiers ingevuld film door de_werknemers	OOC late
Zeg de_klanten dat de_aankopen aangerekend broer aan de_kassa	OOC late
Vraag de_ober of de_bestellingen doorgegeven dochter aan de_keuken	OOC late
Vraag de_loodgieter of de_buizen geplaatst vriendin door zijn_assistent	OOC late
Zeg de_dokter dat zijn_dochter ontvangen wordt in de_klas	PRACTICE
Zeg de_directeur dat de_klas ontruimd is voor het_feest	PRACTICE
Vraag de_vrouw of het_cadeau gevonden werd door haar_hond	PRACTICE
Vraag de_man of zijn_kind gered werd door de brandweer	PRACTICE

APPENDIX 3 : STRUCTURAL PRIMING MATERIALS

In the table below, the 48 pitch sequence primes, which were used in Experiment 2 of Chapter 4, are described by their pitch frequencies and whether they follow an ‘ABA’ or ‘ABB’ structure. Pitch frequencies approach the following tones:

G	(Low)	1959
Ab	(Low)	2076
A	(Low)	2200
B	(Low)	2469
C	(Low)	2616
Db	(Low)	2771
Eb	(Low)	3111
E	(Low)	3296
F	(Low)	3492
G	(High)	3919
Ab	(High)	4153
A	(High)	4400
B	(High)	4938
C	(High)	5232
Db	(High)	5543
Eb	(High)	6222
E	(High)	6592
F	(High)	6984

5232	6984	5232	6222	5543	4153	5232	6984	ABA
1959	2616	1959	4400	4938	6592	2469	2200	ABB
4153	5543	4153	4938	6592	4938	4153	5543	ABA
2469	3296	2200	5542	6222	5542	2076	2771	ABB
6592	4938	6592	3918	5232	3918	6592	4938	ABA
3492	1959	3492	4153	6222	5542	2076	2771	ABB
6592	4938	4400	3918	5232	3918	6592	4938	ABA
2771	2076	2771	6592	4938	4400	2469	2200	ABB

6592	4400	4938	3919	6984	5232	6592	4400	ABA
2469	3296	2469	5543	4153	6222	2771	2076	ABB
4400	4938	4400	5232	3918	5232	4400	4938	ABA
2076	2771	3111	4938	6592	4938	3296	2469	ABB
4400	4938	6592	5232	6984	5232	4400	4938	ABA
3492	2616	3492	4152	5542	4152	2771	2076	ABB
4938	4400	4938	5542	6222	4153	4938	4400	ABA
3492	2616	1959	4152	5542	4152	2771	3111	ABB
3918	5232	3918	4400	4938	4400	3918	5232	ABA
3296	2469	2200	3918	5232	3918	2616	1959	ABB
5543	4153	6222	6592	4938	4400	5543	4153	ABA
1959	3492	2616	4400	6592	4400	2469	3296	ABB
5232	6984	3919	6222	5542	4152	5232	3918	ABA
2076	2771	2076	4938	6592	4400	3296	2469	ABB
4152	5542	4152	4938	4400	4938	4152	5542	ABA
3492	1959	2616	4153	6222	5542	2076	2771	ABB
3918	5232	6984	4400	4938	6592	3918	5232	ABA
3492	2616	3492	4152	5542	6222	2771	3111	ABB
3919	5232	3919	4400	6592	4938	3919	6984	ABA
3111	2771	2076	6984	5232	3919	2616	1959	ABB
6984	3919	5232	4153	6222	4153	6984	3919	ABA
2771	2076	2771	6592	4938	6592	2469	2200	ABB
3919	6984	3919	4400	4938	6592	3919	5232	ABA
3111	2771	2076	6984	5232	3919	2616	3492	ABB
5232	3919	5232	6222	5543	6222	5232	6984	ABA
2469	2200	2469	5543	6222	5543	2076	3111	ABB
4400	6592	4400	5232	3919	6984	4400	4938	ABA
2076	3111	2771	4938	6592	4938	3296	2469	ABB
5542	4152	5542	6592	4938	6592	5542	4152	ABA
3296	2469	2200	3918	5232	3918	2616	1959	ABB
6984	5232	6984	4152	5542	4152	6984	5232	ABA
3296	2200	2469	3919	6984	3919	3492	1959	ABB
6592	4938	6592	3918	5232	3918	6592	4938	ABA
3296	2469	3296	3918	5232	3918	2616	1959	ABB

5232	6984	3919	6222	4153	5543	5232	3918	ABA
2469	3296	2469	5543	4153	6222	2076	2771	ABB
6222	5543	4153	6984	5232	3919	6222	5543	ABA
2771	3111	2076	6592	4400	4938	3296	2469	ABB
6984	5232	6984	4152	5542	6222	6984	5232	ABA
2771	3111	2076	6592	4400	4938	3296	2469	ABB

In the table below, the 48 mathematical equation primes, which were used in Experiment 2 of Chapter 4, reported below. These would also follow an ‘ABA’ or ‘ABB’ structure.

3 + ((6 - 2) / 2) =	ABA
3 + 6 - (2 / 2) =	ABB
80 - ((9 + 1) × 5) =	ABA
80 - 9 + (1 × 5) =	ABB
10 + ((7 - 5) × 3) =	ABA
10 + 7 - (5 × 3) =	ABB
67 - ((24 - 12) / 3) =	ABA
67 - 24 - (12 / 3) =	ABB
40 + ((8 + 2) × 3) =	ABA
40 + 8 + (2 × 3) =	ABB
7 + ((28 - 4) × 2) =	ABA
7 + 28 - (4 × 2) =	ABB
20 + ((36 - 6) / 2) =	ABA
20 + 36 - (6 / 2) =	ABB
9 + ((20 + 10) / 5) =	ABA
9 + 20 + (10 / 5) =	ABB
56 - ((5 + 3) × 2) =	ABA
56 - 5 + (3 × 2) =	ABB
15 - ((12 - 4) / 2) =	ABA
15 - 12 - (4 / 2) =	ABB
31 + ((8 - 5) × 2) =	ABA
31 + 8 - (5 × 2) =	ABB

2 + ((8 + 4) × 3) =	ABA
2 + 8 + (4 × 3) =	ABB
40 - ((18 - 8) / 2) =	ABA
40 - 18 - (8 / 2) =	ABB
85 - ((14 + 21) / 7) =	ABA
85 - 14 + (21 / 7) =	ABB
20 + ((24 - 8) / 4) =	ABA
20 + 24 - (8 / 4) =	ABB
10 + ((6 + 3) × 2) =	ABA
10 + 6 + (3 × 2) =	ABB
90 - ((5 + 15) / 5) =	ABA
90 - 5 + (15 / 5) =	ABB
56 + ((6 + 6) / 2) =	ABA
56 + 6 + (6 / 2) =	ABB
78 - ((9 + 6) × 2) =	ABA
78 - 9 + (6 × 2) =	ABB
4 + ((22 - 4) / 2) =	ABA
4 + 22 - (4 / 2) =	ABB
45 - ((10 + 5) × 3) =	ABA
45 - 10 + (5 × 3) =	ABB
98 - ((50 - 30) / 10) =	ABA
98 - 50 - (30 / 10) =	ABB
70 – ((25 + 5) / 5) =	ABA
70 – 25 + (5 / 5) =	ABB
89 - 3 - (2 × 2) =	ABA
89 - ((3 - 2) × 2) =	ABB

In the table below, the 48 means-end primes, which were used in Experiment 2 of Chapter 4, reported below. These would also follow an ‘ABA’ or ‘ABB’ structure.

John grijpt zijn verrekijker, drinkt een glas wortelsap, en...	ABA
John at een appel, zette de kookplaat aan, en...	ABB

John nam de enveloppe, verslond zijn avondmaal, en...	ABA
John knabbelde op de snack, opende de lade, en...	ABB
John nam zijn camera, plantte de zaadjes, en...	ABA
John waste de auto, sloot zijn usb aan op de pc, en...	ABB
John opende zijn pc, deed de vaat, en...	ABA
John las zijn krant, deed zijn jas aan, en...	ABB
John nam zijn telefoon, streek de hemden, en...	ABA
John jogde rond de watersportbaan, startte de pc op, en...	ABB
John kocht een dvd, speelde een voetbalmatch, en...	ABA
John zwom in de vijver, nam een handdoek, en...	ABB
John kocht een cd, speelde een partijtje golf, en...	ABA
John sprong op de trampoline, zette de tv aan, en...	ABB
John nam zijn controle-formulier, bezocht de attractie, en...	ABA
John keek naar de voetbalmatch, sneed de groentjes, en...	ABB
John kocht wat pasta, speelde een schaakspel, en...	ABA
John ging naar het concert, deed zijn voordeur open, en...	ABB
John zocht het adres op, vulde een sudoku in, en...	ABA
John bekeek zijn mail, haalde een gezelschapsspel boven, en...	ABB
John vulde de formulieren in, keek naar zijn favoriete tv-show, en...	ABA
John luisterde naar de nieuwste radiohit, nam zijn schop, en...	ABB
John sorteerde de was, speelde een videospelletje, en...	ABA
John dronk een tas koffie, krikte de auto omhoog, en...	ABB
John startte de GPS, verstuurde zijn documenten, en...	ABA
John at een snoepje, stak batterijen in zijn tandenborstel, en...	ABB
John nam het recept, dronk een glas wijn, en...	ABA
John waste de tuinmeubelen, startte de kettingzaag, en...	ABB
John stapte op de skipiste, rekte zich uit, en...	ABA
John las zijn boek uit, verzamelde hout, en...	ABB
John nam een handdoek, waste zich zorgvuldig, en...	ABA
John bekeek de film, opende de kast, en...	ABB
John haalde het anker aan boord, at zijn lunch op, en...	ABA
John maakte de tekening af, nam zijn duikmateriaal, en...	ABB
John nam de cake uit de koelkast, speelde een computerspel, en...	ABA
John waste zijn fiets, ontdooide het vlees, en...	ABB

John nam de dweil, dronk wat vruchtensap, en...	ABA
John las zijn mails, vulde een emmer met water, en...	ABB
John waste de sla, groette de buurvrouw, en...	ABA
John maaide het gras, klom op het dak, en...	ABB
John deed zijn sportschoenen aan, ruimde zijn kamer snel op, en...	ABA
John las de post door, nam de schilderverf, en...	ABB
John zocht het telefoonnummer op, nam een snelle douche, en...	ABA
John las het boek uit, vulde de waterkruik, en...	ABB
John nam zijn gsm, kleedde zich aan, en...	ABA
John dweilde de vloer, deed de hond een leiband om, en...	ABB
John opende de verfpot, zette de koffie op, en...	ABA
John at zijn tortilla op, nam zijn agenda, en...	ABB

In the table below, the 48 relative clause attachment primes, which were used in Experiment 2 of Chapter 4, reported below. These sentences are required to be completed following either a high attachment (HA) or low attachment (LA) structure

De secretaris wijzigt het schema van de afwezigheden dat...	HA
De leraar straft het dochtertje van de dokter die...	LA
De directeur leest het briefje van de studente dat...	HA
De apotheker vroeg het voorschrift van de medicijnen die...	LA
De secretaris schreef het verslag van de vergadering dat...	HA
De kunstenaar maakte het logo van de muzikanten die...	LA
De politie vindt het zoontje van de ouders dat...	HA
De school organiseert het galabal van de verenigingen die...	LA
De dirigent straft het neefje van de muzikanten dat...	HA
De man plaatst het bureau van de secretaresses die...	LA
De artiest bewondert het schilderij van de artiesten dat...	HA
De leraar beschrijft het klaslokaal van de studenten die...	LA
De journalist leest het magazine van de arbeiders dat...	HA
De dief steelt het juweel van de koningin die...	LA
De eigenaar verkoopt het restaurant van de zaak dat...	HA

De studente volgt het practicum van de professor die...	LA
De monnik bezoekt het klooster van de nonnen dat...	HA
De secretaresse begroet het diensthoofd van de afdeling die...	LA
De kapper knipt het haar van de meisjes dat...	HA
De schrijnwerker herstelt het scharnier van de poort die...	LA
De pianist speelt het muziekstuk van de academie dat...	HA
De agent onderzoekt het mes van de verdachte die...	LA
De telefoniste belt het filiaal van de ondernemers dat...	HA
De criticus bestelt het gerecht van de chefs die...	LA
De ondernemer bekijkt het verslag van de werknemers dat...	HA
De verdelger verwijdert het nest van de ratten die...	LA
De kok kuist het aanrecht van de leerlingen dat...	HA
De tas bevat het verslag van de getuigen die...	LA
De vakbond beledigt het resultaat van de onderhandelingen dat...	HA
De advocaat ontkent het bewijs van de moorden die...	LA
De artiest bewondert de kleuren van het schilderij die...	HA
De leraar schildert de muren van het klaslokaal dat...	LA
De journalist leest de artikels van het tijdschrift die...	HA
De priester ziet de ramen van het klooster dat...	LA
De dief steelt de kisten van het huis die...	HA
De schoonmaker poetst de bedden van het ziekenhuis dat...	LA
De kapper knipt de vlechten van het meisje die...	HA
De vrouw ziet de broers van het meisje dat...	LA
De ober kuist de tafels van het restaurant die...	HA
De secretaresse zoekt de dossiers van het schoolhoofd dat...	LA
De studente verzamelt de notities van het practicum die...	HA
De kuisvrouw wast de glazen van het raam dat...	LA
De garagist onderzoekt de portieren van het busje die...	HA
De politicus begroet de kiezers van het dorpje dat...	LA
De leraar verbetert de opdrachten van het proefwerk die...	HA
De onderzoeker bestudeert de bewegingen van het model dat...	LA
De bediende verwerkt de documenten van het register die...	HA
De journalist interviewt de getuige van het ongeval dat...	LA

APPENDIX 4: DATA SHEETS AND ANALYSIS SCRIPTS

A folder with all the data files and R-scripts can be freely downloaded from Open Science Framework. They can be found under the project ‘Dissertation: Syntax across Domains: overlap in global and local structure processing’ on the account of Joris Van de Cavey (http://opensciencefamework.org/profile/v49bp).

Chapter 2: Data are represented in file ‘Shared Chapter 2.dat’. A full commented analysis script can be found in the file ‘Shared Chapter 2.r’

Chapter 3: Data for the time windows for all 6 ROI’s are represented in the files ‘200-280-sentence-ROI-6.dat’,’280-340-sentence-ROI-6.dat’,’300-500-sentence-ROI.dat’,’320-380-sentence-ROI.dat’,’500-660-sentence-ROI.dat’,’580-640-sentence-ROI.dat’,’680-740-sentence-ROI.dat’,and ‘740-760-sentence-ROI.dat’. A commented analysis script for these time windows and ROI’s can be found in ‘sentence-ROI-6.r’. The behavioural measures are represented in the data file ‘Alignment ERP behavioural.dat’ and the corresponding analysis file ‘Alignment ERP behavioural.r’

Chapter 4: Data for Experiment 1a can be found in ‘data_experiment_1.dat’, and the corresponding analysis in ‘data_experiment_1_Review.r’. Data for Experiment 1b (i.e., the colour control experiment) can be found in ‘colorcontrol-nofillers.dat’, and the corresponding analysis in ‘data_colorcontrol_Review.r’. The direct comparison of the results in Experiment 1a and 1b is reflected in the data sheet ‘Exp_1andcontrol.dat’ and the analysis script ‘Exp_1andcontrol_Revision.r’. Data for Experiment 2 can be found in the file ‘data_exp_2_Prevtarget.dat’, and the corresponding analysis file ‘data_experiment_2_Review.r’.

Chapter 5: Data for the priming effects reported in chapter 5 can be found in ‘Analysis_Priming_Congruency.dat’ and the corresponding analysis file ‘Analysis_Priming_Congruency.r’.

Appendix 1: The data for the phrasing experiment reported in Appendix 1 can be found in ‘Phrasing Appendix.dat’ and the corresponding analysis file ‘Phrasing Appendix.r’.

DATA STORAGE FACT SHEETS

In compliance with the UGent standard for research accountability, transparency and reproducibility, the location of the datasets used in this dissertation are added below. For each of the empirical chapters (i.e., chapters 2 to 5) a separate Data Storage Fact Sheet is completed, detailing which data and analysis files are stored, where they are stored, who has access to the files and who can be contacted in order to request access to the files. In addition, the Data Storage Fact Sheets have been added to my public UGent Biblio account.

DATA STORAGE CHAPTER 2

```
% Data Storage Fact Sheet

% Name/identifier study
% Author: Joris Van de Cavey
% Date: 17-06-2016


1. Contact details
======================================================
1a. Main researcher
-----------------------------------------------------------
- name: Joris Van de Cavey
- address: Henri Dunantlaan 2 9000 Gent
```

- e-mail: joris.vandecavey@gmail.com or joris.vandecavey@ugent.be

1b. Responsible Staff Member (ZAP)

- name: Robert Hartsuiker
- address: Henri Dunantlaan 2 9000 Gent
- e-mail: robert.hartsuiker@ugent.be

If a response is not received when using the above contact details, please send an email to data.pp@ugent.be or contact Data Management, Faculty of Psychology and Educational Sciences, Henri Dunantlaan 2, 9000 Ghent, Belgium.

2. Information about the datasets to which this sheet applies
===
* Reference of the publication in which the datasets are reported:

Chapter 2 of PhD dissertation (first empirical chapter): Shared Structuring Resources across Domains: Double task effects from linguistic processing on the structural integration of pitch sequences

* Which datasets in that publication does this sheet apply to?:

All data from the reported experiment (behavioral).

3. Information about the files that have been stored
===

3a. Raw data
----

* Have the raw data been stored by the main researcher? [x] YES / [ ] NO
If NO, please justify:

* On which platform are the raw data stored?
- [x] researcher PC
- [ ] research group file server
- [ ] other (specify): ...

* Who has direct access to the raw data (i.e., without intervention of another person)?
- [x] main researcher
- [ ] responsible ZAP
- [ ] all members of the research group
- [ ] all members of UGent
- [ ] other (specify): ...

3b. Other files
----

* Which other files have been stored?
- [ ] file(s) describing the transition from raw data to reported results. Specify: ...
- [X] file(s) containing processed data. Specify: ...
- [X] file(s) containing analyses. Specify: R scripts (containing all processing steps and their justification)
- [X] files(s) containing information about informed consent (printed informed consents stored in folder)
- [X] a file specifying legal and ethical provisions
- [ ] file(s) that describe the content of the stored files and how this content should be interpreted. Specify: ...
- [X] other files. Specify: Data Sheets and Analysis Scripts

* On which platform are these other files stored?
- [x] individual PC
- [ ] research group file server

- [x] other: data sheets and analysis scripts are freely accessible through the Open Science Framework

* Who has direct access to these other files (i.e., without intervention of another person)?
- [x] main researcher
- [x] responsible ZAP
- [x] all members of the research group
- [x] all members of UGent
- [x] other (specify): ...

4. Reproduction
===
* Have the results been reproduced independently?: [ ] YES / [x] NO

* If yes, by whom (add if multiple):
- name:
- address:
- affiliation:
- e-mail:

v0.2

DATA STORAGE CHAPTER 3

% Data Storage Fact Sheet

% Name/identifier study
% Author: Joris Van de Cavey
% Date: 17-06-2016

1. Contact details
===

1a. Main researcher

- name: Joris Van de Cavey
- address: Henri Dunantlaan 2 9000 Gent
- e-mail: joris.vandecavey@gmail.com or joris.vandecavey@ugent.be

1b. Responsible Staff Member (ZAP)

- name: Robert Hartsuiker
- address: Henri Dunantlaan 2 9000 Gent
- e-mail: robert.hartsuiker@ugent.be

If a response is not received when using the above contact details, please send an email to data.pp@ugent.be or contact Data Management, Faculty of Psychology and Educational Sciences, Henri Dunantlaan 2, 9000 Ghent, Belgium.

2. Information about the datasets to which this sheet applies
===

* Reference of the publication in which the datasets are reported:

Chapter 3 of PhD dissertation (second empirical chapter):
Electrophysiological Support for Interactions during the Joint Structural Processing of Linguistic and Non-linguistic Materials

* Which datasets in that publication does this sheet apply to?:

All data from the reported experiment (behavioral).

3. Information about the files that have been stored
===

3a. Raw data
----

* Have the raw data been stored by the main researcher? [x] YES / [ ] NO
If NO, please justify:

* On which platform are the raw data stored?
- [x] researcher PC
- [ ] research group file server
- [ ] other (specify): ...

* Who has direct access to the raw data (i.e., without intervention of another person)?
- [x] main researcher
- [ ] responsible ZAP
- [ ] all members of the research group
- [ ] all members of UGent
- [ ] other (specify): ...

3b. Other files
----

* Which other files have been stored?
- [ ] file(s) describing the transition from raw data to reported results. Specify: ...
- [X] file(s) containing processed data. Specify: ...
- [X] file(s) containing analyses. Specify: R scripts (containing all processing steps and their justification)
- [X] files(s) containing information about informed consent (printed informed consents stored in folder)
- [X] a file specifying legal and ethical provisions
- [ ] file(s) that describe the content of the stored files and how this content should be interpreted. Specify: ...
- [X] other files. Specify: Data Sheets and Analysis Scripts

* On which platform are these other files stored?
- [x] individual PC
- [ ] research group file server
- [x] other: data sheets and analysis scripts are freely accessible through the Open Science Framework

* Who has direct access to these other files (i.e., without intervention of another person)?
- [x] main researcher
- [x] responsible ZAP
- [x] all members of the research group
- [x] all members of UGent
- [x] other (specify): ...

4. Reproduction
===
* Have the results been reproduced independently?: [ ] YES / [x] NO

* If yes, by whom (add if multiple):
- name:
- address:
- affiliation:
- e-mail:

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DATA STORAGE CHAPTER 4

% Data Storage Fact Sheet

% Name/identifier study
% Author: Joris Van de Cavey
% Date: 17-06-2016

1. Contact details
===

1a. Main researcher

- name: Joris Van de Cavey
- address: Henri Dunantlaan 2 9000 Gent
- e-mail: joris.vandecavey@gmail.com or joris.vandecavey@ugent.be

1b. Responsible Staff Member (ZAP)

- name: Robert Hartsuiker
- address: Henri Dunantlaan 2 9000 Gent
- e-mail: robert.hartsuiker@ugent.be

If a response is not received when using the above contact details, please send an email to data.pp@ugent.be or contact Data Management, Faculty of Psychology and Educational Sciences, Henri Dunantlaan 2, 9000 Ghent, Belgium.

2. Information about the datasets to which this sheet applies
===

* Reference of the publication in which the datasets are reported:

Chapter 4 of PhD dissertation (third empirical chapter): Evidence for Structural Priming across Music, Math, Action descriptions and Language

* Which datasets in that publication does this sheet apply to?:

All data from the reported experiment (behavioral).

3. Information about the files that have been stored
===

3a. Raw data
----

* Have the raw data been stored by the main researcher? [x] YES / [ ] NO
If NO, please justify:

* On which platform are the raw data stored?
- [x] researcher PC

- [ ] research group file server
- [ ] other (specify): ...

* Who has direct access to the raw data (i.e., without intervention of another person)?
- [x] main researcher
- [ ] responsible ZAP
- [ ] all members of the research group
- [ ] all members of UGent
- [ ] other (specify): ...

3b. Other files
----

* Which other files have been stored?
- [ ] file(s) describing the transition from raw data to reported results. Specify: ...
- [X] file(s) containing processed data. Specify: ...
- [X] file(s) containing analyses. Specify: R scripts (containing all processing steps and their justification)
- [X] files(s) containing information about informed consent (printed informed consents stored in folder)
- [X] a file specifying legal and ethical provisions
- [ ] file(s) that describe the content of the stored files and how this content should be interpreted. Specify: ...
- [X] other files. Specify: Data Sheets and Analysis Scripts

* On which platform are these other files stored?
- [x] individual PC
- [ ] research group file server
- [x] other: data sheets and analysis scripts are freely accessible through the Open Science Framework

```
* Who has direct access to these other files (i.e., without intervention of another person)?
- [x] main researcher
- [x] responsible ZAP
- [x] all members of the research group
- [x] all members of UGent
- [x] other (specify): ...

4. Reproduction
=====================================================
* Have the results been reproduced independently?: [ ] YES / [x] NO

* If yes, by whom (add if multiple):
- name:
- address:
- affiliation:
- e-mail:


v0.2
```

DATA STORAGE CHAPTER 5

```

% Data Storage Fact Sheet

% Name/identifier study
% Author: Joris Van de Cavey
% Date: 17-06-2016
```

1. Contact details
===

1a. Main researcher

- name: Joris Van de Cavey
- address: Henri Dunantlaan 2 9000 Gent
- e-mail: joris.vandecavey@gmail.com or joris.vandecavey@ugent.be

1b. Responsible Staff Member (ZAP)

- name: Robert Hartsuiker
- address: Henri Dunantlaan 2 9000 Gent
- e-mail: robert.hartsuiker@ugent.be

If a response is not received when using the above contact details, please send an email to data.pp@ugent.be or contact Data Management, Faculty of Psychology and Educational Sciences, Henri Dunantlaan 2, 9000 Ghent, Belgium.

2. Information about the datasets to which this sheet applies
===
* Reference of the publication in which the datasets are reported:

Chapter 5 of PhD dissertation (fourth empirical chapter): Priming beyond Language : continuation of structural preferences in the processing of non-linguistic auditory sequences

* Which datasets in that publication does this sheet apply to?:

All data from the reported experiment (behavioral).

3. Information about the files that have been stored

===

3a. Raw data

----

* Have the raw data been stored by the main researcher? [x] YES / [ ] NO
If NO, please justify:

* On which platform are the raw data stored?
- [x] researcher PC
- [ ] research group file server
- [ ] other (specify): ...

* Who has direct access to the raw data (i.e., without intervention of another person)?
- [x] main researcher
- [ ] responsible ZAP
- [ ] all members of the research group
- [ ] all members of UGent
- [ ] other (specify): ...

3b. Other files

----

* Which other files have been stored?
- [ ] file(s) describing the transition from raw data to reported results. Specify: ...
- [X] file(s) containing processed data. Specify: ...
- [X] file(s) containing analyses. Specify: R scripts (containing all processing steps and their justification)
- [X] files(s) containing information about informed consent (printed informed consents stored in folder)
- [X] a file specifying legal and ethical provisions

- [ ] file(s) that describe the content of the stored files and how this content should be interpreted. Specify: ...
- [X] other files. Specify: Data Sheets and Analysis Scripts

* On which platform are these other files stored?
- [x] individual PC
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- [x] other: data sheets and analysis scripts are freely accessible through the Open Science Framework

* Who has direct access to these other files (i.e., without intervention of another person)?
- [x] main researcher
- [x] responsible ZAP
- [x] all members of the research group
- [x] all members of UGent
- [x] other (specify): ...

4. Reproduction

===

* Have the results been reproduced independently?: [ ] YES / [x] NO

* If yes, by whom (add if multiple):
- name:
- address:
- affiliation:
- e-mail:

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