- 1 Hierarchical control as a shared neurocognitive mechanism for language and music
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#### Abstract

Although comparative research has made substantial progress in clarifying the relationship between language and music as neurocognitive systems from both a theoretical and empirical perspective, there is still no consensus about which mechanisms, if any, are shared and how they bring about different neurocognitive systems. In this paper, we tackle these two questions by focusing on hierarchical control as a neurocognitive mechanism underlying syntax in language and music. We put forward the Coordinated Hierarchical Control (CHC) hypothesis: linguistic and musical syntax rely on hierarchical control, but engage this shared mechanism differently depending on the current control demand. While linguistic syntax preferably engages the abstract rule-based control circuit, musical syntax rather employs the coordination of the abstract rule-based and the more concrete motor-based control circuits. We provide evidence for our hypothesis by reviewing neuroimaging as well as neuropsychological studies on linguistic and musical syntax. The CHC hypothesis makes a set of novel testable predictions to guide future work on the relationship between language and music.

### Keywords

- 26 Hierarchical control, Neurocognitive mechanism, Linguistic syntax, Musical syntax,
- 27 Abstraction gradient, Cortico-basal ganglia-thalamocortical circuit

#### 1 Introduction

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Hierarchical cognitive control (hereafter "hierarchical control") is a neurocognitive mechanism that captures a set of control processes guiding thought and action on the basis of intentions, plans, and goals to enable flexible behavior (Badre & D'Esposito, 2009; Koechlin & Summerfield, 2007). The key idea of hierarchical control is that those control processes are hierarchically organized to select, maintain, and inhibit progressively abstract and temporally extended goals (Badre, 2008; Badre & D'Esposito, 2009; Koechlin & Summerfield, 2007). The goal representations and control processes are hierarchically organized in such a way that the more abstract levels determine the more concrete levels. For example, to execute and understand a complex action (e.g., making coffee), goals should be selected, maintained, and inhibited at multiple hierarchical levels ranging from the abstract, temporally extended goal (e.g., making coffee) to the sub-goals (e.g., filling a pot with water) and to concrete motor acts (e.g., grabbing the pot). We understand a mechanism as composed of different constituent parts performing unique operations and working in tandem to bring about a given phenomenon (Bechtel & Shagrir, 2015). Hierarchical control is a neurocognitive mechanism because its constituent parts (selection, maintenance, and inhibition) build an interface between cognitive and neural operations (Badre & Frank, 2012; Frank, Loughry, & O'Reilly, 2001).

As suggested by Lashley (1951), in a similar way to action, language and music cannot be explained by associative chain theories whereby one element (e.g., movement, word, or note) serially triggers the next one. Rather, there should be a generalized pattern (called 'syntax' or 'schema') to hierarchically process linguistic and musical sequences. Thus, hierarchical control is not only a neurocognitive mechanism underlying action, but also language and music (Fitch & Martins, 2014; Jeon, 2014; Slevc & Okada, 2015; Uddén & Bahlmann, 2012). However, linguistic and musical syntax differ in items to be combined, categories to be labeled, and contents to be encoded (Asano & Boeckx, 2015; Patel, 2008), and it is not clear how this shared neurocognitive mechanism relate to such differences.

One possible explanation was provided by the "resource sharing framework" (Patel, 2003, 2013). This framework suggests that linguistic and musical syntax engage a set of shared neurocognitive processes implemented in the frontal regions and those shared processes operate on domain-specific long-term memory representations in the temporal regions via functional connections between those two regions. In the current paper, we offer a complementary approach, and highlight the oft-neglected fact that even shared processes are utilized differently in processing linguistic and musical syntax. We frame this in terms of a gradient between more abstract temporally extended control and more concrete motor control (hereafter "abstraction gradient"). In processing linguistic and musical sequences, their representations are temporarily maintained, selected, and inhibited at hierarchical levels differing in abstractness to flexibly adapt to the current control demand in a way similar to what we illustrated above for goal representations. Thus, our focus is temporarily stored representations and corresponding processes.

The concepts of abstraction gradient and control demand stem from research on cognitive control. In the literature on cognitive control, control demands are a function of the hierarchical depth of contextual representations and the time span for maintaining contextual representations, which directly corresponds to the degree of abstraction (Badre, 2008; Badre & Nee, 2018). For example, selecting a motor response based on a contextual cue (e.g., geometric shape), which in turn depends on another contextual cue (e.g., color), is more demanding than selecting a motor response based on a contextual cue without any further contextual representations. In this case, the color cue is considered to be more abstract than the shape cue as it does not directly govern the motor response, but instead governs another contextual cue. This type of abstraction in which context generalizes over differently abstract stimulus-response rules is known as "policy abstraction", where a policy is considered to be akin to a rule (Badre & Nee, 2018). Another type of abstraction concerns "temporal abstraction": contextual representations are maintained over time and span intervening episodes or subtasks as

overarching goal representations (Badre & Nee, 2018). Performing complex actions such as coffee making requires both types of abstraction.

Similarly, we suggest that linguistic and musical syntax involve different levels of policy (or rule) and temporal abstraction depending on the hierarchical depth and the span of representations to be maintained, selected, and inhibited. For example, linguistic syntax interfaces with conceptual (i.e., semantic) and sensory-motor (i.e., phonological) systems, and thus differently engage more abstract and more concrete control processes to link meaning and sound in processing sentences. This is related to an abstraction gradient from semantics to syntax to phonology suggested by Uddén & Bahlmann (2012). Musical syntax (Box 1) – tonalharmonic and rhythmic syntax – links affect and sound at different levels of abstraction. While affect can be directly linked to the sensory-motor system, it can also represent more abstract, schematic patterns of tension and relaxation (Lerdahl, 2013). Moreover, sentences and musical sequences with center-embedding calls for high control demand and require temporal abstraction (Jeon, 2014). Relevant examples include sentences with center-embedded relative clauses such as "[Researchers [who work hard and sleep little]EMBEDDED CLAUSE need a lot of coffee. MAIN CLAUSE" and chord progressions with embedding of one key inside another (i.e., modulation) (see the famous Bach's "Little Harmonic Labyrinth" (BWV 591) example by Hofstadter, 1979; see also Rohrmeier, 2011). In any case, the greater the hierarchical and temporal distance between contextual and sensory-motor representations is, the more the current control demand becomes.

**Box 1 Musical syntax** 

A core function of musical syntax is mapping between hierarchically structured representation and sequence to link sound and affect, i.e., tension-relaxation patterns (Lerdahl & Jackendoff, 1983). Musical syntax includes at least two subcomponents, namely tonal-harmonic syntax and rhythmic syntax (Asano & Boeckx, 2015). Tonal-harmonic syntax links sound and affect on the basis of tonal hierarchy which represents stability relationships between pitches. Relative importance of pitches is determined in relation to the most stable and important pitch. Rhythmic syntax links sound and affect on the basis of hierarchical metrical and grouping structure. Metrical structure represents relative prominence of beats, while grouping structure represents musical units such as motives, phrases, and sections. Relative salience of beats is determined

by interaction between metrical and grouping structure. Each musical style or culture may possesses its own characteristic rules incorporating tonal and rhythmic hierarchy to establish relationship between elements, but tension-relaxation patterns are considered to be a more general principle common to any musical style and culture (Jackendoff & Lerdahl, 2006; Lerdahl, 2013).

Moreover, "musical syntax" is often used to denote a formal characterization of tonal-harmonic structure (Rohrmeier, 2007, 2011). However, musical rhythm is an organizing principle of music (Patel, 2008) and thus is an integrative part of musical syntax as well (Asano & Boeckx, 2015; Fitch, 2013; Longuet-Higgins & Lee, 1984). More specifically, rhythmic syntax yields different strengths of syncopation and polyrhythmic layers on the basis of metrical hierarchy (Fitch, 2013, 2016; Longuet-Higgins & Lee, 1984). Thus, although musical rhythm can be compared to speech rhythm in terms of metrical structure, it features more elaborated hierarchical structures (Asano & Boeckx, 2015; Jackendoff, 2009). When referring to the brain circuits involved, tonal-harmonic and rhythmic syntax both activates the inferior frontal gyrus as a common denominator (**Figure 2** and **Table 1** of **Section 2.1.1**), while musical pitch processing additionally engages the right fronto-temporal network (Peretz, 2013) and musical rhythm processing employs the network of motor-related cortical and subcortical regions (Leow & Grahn, 2014; Merchant, Grahn, Trainor, Rohrmeier, & Fitch, 2015). Thus, we treat tonal-harmonic and rhythmic syntax together as musical syntax by focusing on their abstract hierarchical structure although we are aware of the important differences between the two.

In Section 2, based on those concepts of abstraction gradient and control demand, we introduce a hypothesis elucidating the relationship between linguistic and musical syntax in terms of hierarchical control, provide supportive evidence from neuroimaging and neuropsychological studies, and present testable predictions of our hypothesis. In Section 3, we then discuss the previous findings from comparative research on linguistic and musical syntax in light of our hypothesis. Although we acknowledge that prosody is hierarchically organized, can be described trough formal rules, influences linguistic syntactic processing, and parallels some aspects of musical syntax (for discussions, see Fabb & Halle, 2012; Heffner & Slevc, 2015), our hypothesis does not treat the relationship between prosody and musical syntax because empirical studies investigating its relationship in terms of hierarchical processing is too sparse at the moment. But we briefly come back to this issue in Section 4.

# 2 The Coordinated Hierarchical Control (CHC) hypothesis: Same neurocognitive

#### mechanism but different use

Our hypothesis concerning the relationship between linguistic and musical syntax states that both rely on hierarchical control as an orchestration of the prefrontal maintenance function and the basal ganglia dual control functions (i.e., selection and inhibition), yielding a flexible top-down control from more abstract onto more concrete processes and representations on an abstraction gradient. At the same time, our hypothesis also states that linguistic and musical syntax differ in the extent to which they utilize this shared mechanism on the abstraction gradient: Linguistic and musical syntax involve different coordination of more abstract temporally extended control and more concrete motor control to flexibly adapt to the current control demand. As we will argue below, linguistic syntax preferably engages the abstract rule-based control circuit, while musical syntax rather employs the coordination of the abstract rule-based and the more concrete motor-based control circuits. Hereafter, we refer to this hypothesis as "Coordinated Hierarchical Control" (CHC) hypothesis.

The CHC hypothesis rests upon the brain bases of hierarchical control including the prefrontal cortex and its interplay with the basal ganglia in form of the cortico-basal ganglia-thalamocortical (CBGT) circuits (Badre & Nee, 2018; Jeon & Friederici, 2015) (Figure 1). The prefrontal cortex is functionally organized to form an abstraction gradient and functions as a buffer to temporarily maintain representations at differently abstract hierarchical levels (Badre, 2008). More anterior (i.e., rostral) regions of the frontal cortex process more abstract goals and rules, while more posterior (i.e., caudal) regions process more concrete representations which more closely relate to the actual motor outputs. In addition, the more anterior regions for abstract processing influence the more posterior regions for concrete motor processing via the CBGT circuits (Badre & Nee, 2018). In this way, brain regions carrying out more abstract processing influence regions performing more concrete motor processing to bring about complex and flexible goal-directed behaviors in time.

Equally important, the basal ganglia play a crucial role in hierarchical control to select and inhibit cortically maintained (goal) representations at different hierarchical levels, through their dual control functions yielded by coordinated activity of the direct and indirect pathway (P. Lieberman, 2002; Marsden & Obeso, 1994). On the one hand, the basal ganglia assist execution of cortically driven predictable and automatic motor and cognitive patterns by selecting them via the direct pathway. On the other hand, they adapt to unusual circumstances by interrupting and altering the automatically processed motor and cognitive representations through inhibition via the indirect pathway. The topologically organized parallel CBGT circuits reflect the abstraction gradient and enable selection and inhibition of cortically maintained representations at each hierarchical level, while the integrative circuits enable communication of information from different cortical regions to flexibly adapt to the current control demand (Haber, 2003, 2016; Marvel, Morgan, & Kronemer, 2019).

Examples of predictable and automatic motor patterns are practiced and overlearned movements and skills such as driving a car. Once mastered, the procedure for driving a car runs automatically unless a new situation (e.g., a pedestrian on the road) appears to which one should adapt by interrupting the ongoing act and selecting a new strategy (e.g., putting on the brake). Similarly, once syntactic rules of language and music are acquired, linguistic and musical syntactic processing largely runs automatically. However, the automatic processing should be interrupted and altered when structures built so far do not fit to incoming elements and need an update. This could happen in processing unexpected, ambiguous or complex sequences.

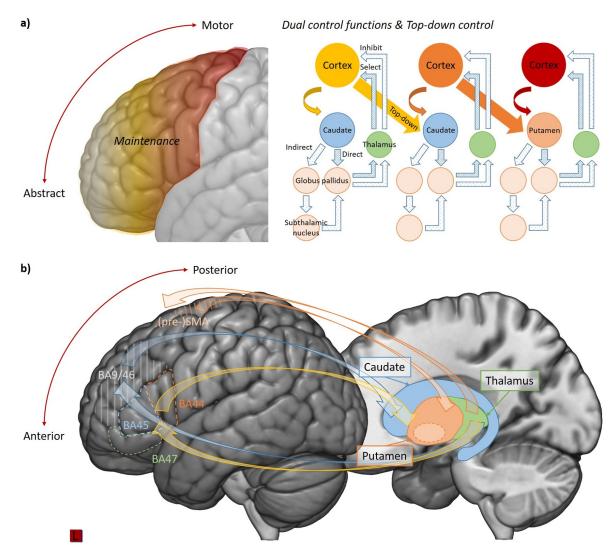


Figure 1 Brain bases of hierarchical control. a) The prefrontal cortex is organized to form an anterior-posterior gradient of abstraction. There are top-down influences from anterior regions processing more abstract representations onto posterior regions processing more concrete representations via the cortico-basal ganglia-thalamocortical (CBGT) circuits. The direct pathway selects and the indirect pathway inhibits cortically maintained representations. b) The CBGT circuits consist of functionally segregated and topographically organized parallel circuits. In this figure, three parallel circuits central to the current paper are displayed. *Motor* circuit (orange arrow): the motor cortex and the supplementary motor area (SMA) are mainly directed to the posterior putamen whereas pre-SMA projections are directed to more anterior parts of the striatum (Lehéricy, Ducros, Krainik, et al., 2004; Lehéricy, Ducros, Van De Moortele, et al., 2004). Executive circuit (blue arrow): cortical projections from the dorsolateral prefrontal cortex including BA9/46 terminate within the anterior striatum and the caudate head (Lehéricy, Ducros, Van De Moortele, et al., 2004). Inferior frontal circuit (yellow arrow): cortical projections from the inferior frontal gyrus (IFG) including BA44, 45, and 47 terminate within the head of caudate and the anterior putamen (Catani et al., 2012; Croxson, 2005; Ford et al., 2013; Leh, Ptito, Chakravarty, & Strafella, 2007; Lehéricy, Ducros, Van De Moortele, et al., 2004). The CBGT circuits also include mechanisms (so-called "integrative circuits") enabling information flow through the adjacent and non-adjacent parallel circuits (Haber, 2003, 2016).

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Our CHC hypothesis expands on an earlier hypothesis proposed by Slevc and Okada (2015), according to which prefrontal cognitive control recruited for conflict detection and resolution is a shared mechanism underlying language and music. First, by focusing on hierarchical control, we put more emphasis on the hierarchical aspect of cognitive control in terms of the abstraction gradient and the top-down control. Hierarchy is a key property shared by linguistic and musical syntax, which – we suggest – is processed by hierarchical control as the shared neurocognitive mechanism. Second, we take advantage of the finding that the basal ganglia work in tandem with the frontal cortex to bring about hierarchical control and suggest that not only the prefrontal cortex, but also the basal ganglia house the neurocognitive mechanism shared in linguistic and musical syntax. This allows our hypothesis to articulate the shared mechanism in terms of maintenance function in the prefrontal cortex and the dual control functions (i.e., selection and inhibition) of the basal ganglia. Third, the CHC hypothesis also accounts for the difference between linguistic and musical syntax by stating that they exert the same mechanism differently.

## 2.1 Neuroimaging and neuropsychological data consistent with the CHC hypothesis

In this section, we provide evidence for the CHC hypothesis by reviewing neuroimaging as well as neuropsychological studies revealing how linguistic and musical syntax employ hierarchical control implemented in the CBGT circuits. Taking the inferior frontal gyrus (IFG) and the (pre-)supplementary motor area ((pre-)SMA) as the candidate shared frontal regions (Cona & Semenza, 2017; Fitch & Martins, 2014; Heard & Lee, 2020; Slevc & Okada, 2015), our focus is on the inferior frontal and the motor circuit and how those two circuits are coordinated differently to implement linguistic and musical syntax. Functionally, the putamen is associated preferentially with sensory-motor chunk-based processes, while the caudate nucleus (hereafter just "caudate") is more related to abstract rule-based processes (M. D. Lieberman, Chang, Chiao, Bookheimer, & Knowlton, 2004). This leads to the conclusion that abstract rule-based control

is implemented in the caudate-based circuits, while sensory-motor chunk-based control is realized in the putamen-based circuits.

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#### 2.1.1 Frontal cortex and abstraction gradient

According to our CHC hypothesis, both linguistic and musical syntax make use of functional organization in the frontal cortex to maintain more abstract representations in the more anterior regions and more concrete representations in the more posterior regions. If this is true, neuroimaging studies investigating linguistic and musical syntax should show activations alongside the abstraction gradient depending on the current control demand.

Concerning linguistic syntax, at least two meta-analyses report IFG activations extending from BA44 via BA45 to BA47 (Heard & Lee, 2020; Zaccarella, Schell, & Friederici, 2017), indicating that a considerable number of neuroimaging studies on linguistic syntax report the IFG activations outside BA44. This seems to be in contrast with the view regarding BA44 as the core neural substrate for linguistic syntax (e.g., Friederici, 2019). However, once the degree of automaticity is taken into account, this apparent paradox can be resolved: in processing sentences, while the activation of highly automatic syntactic processing is confined to BA44, the activations of other IFG subparts play a crucial role for more controlled syntactic processing with low degree of automaticity (Jeon & Friederici, 2015). The automatic processing deals with highly regularized / overlearned rule-based processing, while controlled syntactic processing requires inhibition of automatically engaged syntactic representations and selection of alternatives based on rules. For example, in the context of second language (L2) syntactic processing, which is non-automatic and requires controlled syntactic processing, the increasing levels of hierarchy (reflected in the distance of the elements to be related, i.e., temporal abstraction) showed more and more anterior activations in the IFG (Jeon, Anwander, & Friederici, 2014). In contrast, adult first language (L1) processing, which mostly runs automatically, showed confined activation in BA44 even with the increasing levels of hierarchy (Makuuchi, Bahlmann, Anwander, & Friederici, 2009). Thus, linguistic syntax draws on the abstraction gradient within the IFG in controlled syntactic processing.

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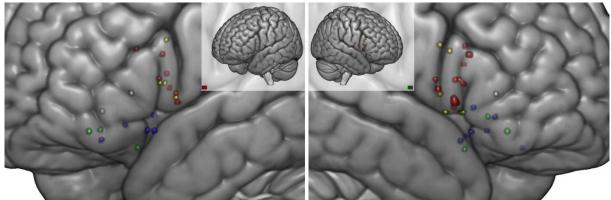
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Activations in the IFG, especially in BA44 and BA47, are also reported in a number of neuroimaging studies investigating musical syntax (Figure 2 and Table 1). One possible interpretation of the extended IFG activations is that BA44 is involved in establishing structural relationship between units, while BA47 is rather engaged in processing affect (Koelsch, 2019). For example, several neuroimaging experiments showed that BA44 is consistently more activated in experimental conditions including music syntactic violations, i.e., when more neural resources are required to establish structural relationship between units (e.g., Herdener et al., 2014; Musso et al., 2015). BA47 is activated when a clear tension-relaxation pattern can be built by cadence (e.g., Fujisawa & Cook, 2011; Seger et al., 2013) or tension is created by expectancy violation or by ambiguity of polyrhythm (e.g., Mayville, Jantzen, Fuchs, Steinberg, & Kelso, 2002; Musso et al., 2015; Vuust, Roepstorff, Wallentin, Mouridsen, & Østergaard, 2006). Nevertheless, the nature of the IFG activation patterns in terms of the abstraction gradient still requires clarification by means of experiments systematically manipulating the control demand. One study on processing of musical sequence with center-embedding rather showed that the level of embedding (reflected in the distance of the elements to be related, i.e., temporal abstraction) is associated with the abstraction gradient of the SMA, i.e., the pre-SMA for two levels of embedding and the SMA for one level of embedding (Cheung, Meyer, Friederici, & Koelsch, 2018). The pre-SMA and SMA are also known as representing time scales larger and smaller than a second, respectively (Schwartze, Rothermich, & Kotz, 2012). Overall, the available data are still consistent with the CHC hypothesis: neuroimaging studies investigating musical syntax show activations along the abstraction gradient.



**Figure 2 Inferior frontal gyrus activations in tonal-harmonic and rhythmic syntax.** On the basis of **Table 1**, the peak activation foci are plotted at the surface by using a Montreal Neurological Institute (MNI) template provided by MRIcrogl (https://www.mccauslandcenter.sc.edu/mricrogl/). The foci reported in Talairach space were transformed into MNI space by using GingerALE (http://www.brainmap.org/ale/). Red = tonal-harmonic syntax in BA44; Yellow = rhythmic syntax in BA44; Light gray = tonal-harmonic and rhythmic syntax in BA45; Blue = tonal-harmonic syntax in BA47; Green = rhythmic syntax in BA47.

Table 1 Studies on tonal-harmonic and rhythmic syntax reporting the inferior frontal gyrus activations. The neuroimaging studies on tonal-harmonic syntax were searched by using PubMed and Google Scholar with "Music AND Syntax", "Music AND Structure", "Music AND Grammar", "(music OR pitch OR melody OR harmony) AND (syntax OR structure)", and "music AND tension" as search criteria (Date: July 19, 2018). The neuroimaging studies on rhythmic syntax were searched by using PubMed and Google Scholar with "syncopation", "music rhythm", and "music beat" as search criteria (Date: December 29, 2018). We report here studies only which provided Talairach (TAL) or Montreal Neurological Institute (MNI) coordinate data. Abbreviations: electroencephalography (EEG); functional magnetic resonance imaging (fMRI); magnetoencephalography (MEG)

Authors (Year)	thors (Year) Method Contrasts		Coordinates (x, y, z)						
(BA6/)BA44(/BA45)									
Tonal-harmonic syntax									
Bianco et al. (2016)	fMRI	incongruent > congruent	MNI	44	18	16			
Cheung et al. (2018)	fMRI	ungrammatical > grammatical	MNI	51	17	10			
Fujisawa & Cook	fMRI	cadence > white noise	TAL	46	16	14			
(2011)			TAL						
Garza Villarreal et al.	EEG	EEG irregular – regular		-37	15	24			
(2011)				37	15	24			
Koelsch et al. (2002)	fMRI modulation > in-key		TAL	46	13	8			
				43	14	28			
		cluster > in-key		-50	10	9			
				-44	7	23			
				46	12	6			
				40	15	25			
Koelsch et al. (2005)	fMRI	irregular > regular	TAL	-55	10	7			
				52	9	11			
Maess et al. (2001)	MEG	irregular – regular	TAL	-48	9	16			
				50	6	14			
Musso et al. (2015)	fMRI		MNI	-54	18	9			

		structural deviant > well- formed		54	18	9
Schmithorst et al. (2005)	fMRI	melody > random tones	TAL	42	11	5
Tillmann et al. (2003)	fMRI	unrelated – related	MNI	-52	8	0
				49	15	0
Tillmann et al. (2006)	fMRI	less related – related	TAL	43	15	3
Rhythmic syntax					1	ı
Chen et al. (2008a)	fMRI	anticipatory listening >	MNI	-54	10	2
, , , , ,		silence		-46	10	26
Chen et al. (2008b)	fMRI	covariation with complexity	MNI	50	12	-4
Danielsen et al. (2014)	fMRI	deviation (drum break) > normal	MNI	46	8	24
Herdener et al. (2014)	fMRI	timing deviation > syncopation	TAL	-46	11	11
Konoike et al. (2012)	fMRI	rhythm encoding > number	TAL	-50	10	12
		encoding		54	12	26
Kung et al. (2013)	fMRI	beat finding > listen isochronous	MNI	56	12	4
		BA45				
Tonal-harmonic synta	Y	DATS				
Koelsch et al. (2005)	fMRI	irregular > regular	TAL	-46	24	10
(2000)		11080101 1080101	1112	44	29	12
Rhythmic syntax	1		<u> </u>			
Konoike et al. (2012)	fMRI	rhythm encoding > number	TAL	-28	28	2
		encoding				
		(BA45/)BA47(/Insula)				
Tonal-harmonic synta		1. 1. 1. 1. 1. 1.	MOII	1.5	22	
Cheung et al. (2018)	fMRI	ungrammatical > grammatical	MNI	45	32	-6
Fedorenko et al. (2012)	fMRI	intact > scrambled	MNI	18	34	-20
Fujisawa & Cook	fMRI	cadence > white noise	TAL	-30	19	-4
(2011)				34	23	-3
Koelsch et al. (2005)	fMRI	irregular > regular	TAL	-41	16	-6
- 4 (2012)	2			47	19	-6
Lehne et al. (2013)	fMRI	tension regressor	MNI	-39	38	-17
Levitin & Menon	fMRI	normal > scrambled	TAL	-48	16	-6
(2003)	AMDI		MOH	44	16	-8
Musso et al. (2015)	fMRI	structural deviant > well- formed	MNI	48	24	-3
Seger et al. (2013)	fMRI	cadences > music baseline	TAL	-44	14	-1
				45	22	-3
Rhythmic syntax		1	I · -			
Chapin et al. (2010)	fMRI	attend to auditory rhythm > rest	TAL	-30 34	15 15	-12 -12
Kung et al. (2013)	fMRI	beat finding > listen	MNI	50	20	-4
		isochronous				
Mayville et al. (2002)	fMRI	syncopation >	TAL	38	25	1
X7	O (D)	synchronization	T . T	26	20	
Vuust et al. (2006)	fMRI		TAL	36	32	-2

		tap main meter (M) to counter		-30	32	-4
		meter > tap M to M				
Vuust et al. (2011)	fMRI	tap counter meter > tap meter	TAL	-42	42	-4

## 2.1.2 Top-down control via the cortico-basal ganglia-thalamocortical (CBGT) circuits

The CHC hypothesis suggests that, in processing sentences or musical sequences, the abstract levels influence the lower levels from the top down via the CBGT circuits. If this is the case, neuroimaging studies investigating linguistic and musical syntax should show the abstraction gradient in the interplay between the frontal cortex and the basal ganglia. In addition, the information should flow from the anterior to the posterior frontal regions via the basal ganglia. Furthermore, linguistic and musical syntax should differ in the extent to which they engage the inferior frontal and the motor circuit.

As for linguistic syntax, a neuroimaging study shows the abstraction gradient in the inferior frontal circuit depending on the current control demand. Processing long-distance dependency in L2 engages the caudate head together with BA47, while processing adjacent dependency activated the caudate body together with BA45 (Jeon et al., 2014). Further neuroimaging experiments also showed that the IFG including the BA44, BA45, and BA47 as well as the caudate are involved in syntactic (i.e. word order) anomaly recognition in pseudoword sentences (Moro et al., 2001), processing syntactically ambiguous sentences (Stowe, Paans, Wijers, & Zwarts, 2004), and acceptability judgement of ungrammatical and ambiguous sentences (Mestres-Missé, Turner, & Friederici, 2012). Moreover, a computational model (Dominey & Inui, 2009) demonstrated that the IFG shows top-down control in linguistic syntax such that the more anterior regions (BA47/45) influence the more posterior regions (BA45/44) via the caudate. An extension of this model successfully simulated P600, i.e., an event-related potential (ERP) component which is associated with controlled syntactic processing (Hinaut & Dominey, 2013). By using this extended model, Szalisznyó and colleagues (2017) simulated the result of the voxel-based lesion symptom mapping study by

Teichmann and colleagues (2015) which showed that the fiber tract connecting Broca's region and the caudate plays a central role in controlled syntactic processing. Thus, the available data are consistent with the claim that linguistic syntax employs the abstraction gradient within the inferior frontal circuit to flexibly adapt to the current processing demand through the top-down control from the more anterior regions of the IFG onto the more posterior regions.

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While the studies reviewed so far suggest that linguistic syntax preferably engages the inferior frontal circuit in controlled syntactic processing, there is also evidence that linguistic syntax involves the putamen and the motor circuit when more sensory-motor chunk-based control is required. One study which investigated the processing of Jabberwocky sentences (i.e., sentences made up of pseudowords) showed the left BA44/45 and the right caudate activation as well as the left pre-SMA and the right putamen activation (Bonhage, Mueller, Friederici, & Fiebach, 2015). It is possible that the top-down control from syntactic rule-based processes onto speech motor control and sequencing plays a central role in processing Jabberwocky sentences as they include syntactic and phonological information, but lack lexical-semantic information. The pre-SMA is crucial for sequencing in linguistic syntax (Cona & Semenza, 2017; Hertrich, Dietrich, & Ackermann, 2016). Speech motor control and sequencing also engage the putamen, the caudate, and the motor CBGT circuit (Guenther, 2016). In another study that contrasted Jabberwocky sentence processing to phonological processing, only the inferior frontal circuit activation was reported (Moro et al., 2001). That is, linguistic syntax preferably engages the inferior frontal circuit, but involves the coordination of this circuit with the motor circuit if the current control demand is of the more concrete, sensory-motor chunk-based type.

Concerning musical syntax, activations of the caudate together with the IFG are reported in tonal-harmonic syntax (Fujisawa & Cook, 2011; Koelsch, Fritz, & Schlaug, 2008; Koelsch et al., 2002; Musso et al., 2015; Seger et al., 2013; Tillmann et al., 2003) as well as in rhythmic syntax (Kung et al., 2013; Mayville et al., 2002) in processing rule-based expectancies and expectancy violations. At least two of those studies (Kung et al., 2013; Musso et al., 2015)

reported activations in BA47, Broca's region and the caudate together, which is consistent with the CHC hypothesis concerning the gradient within the inferior frontal circuit. Although a detailed inquiry is still necessary, it is possible that musical syntax engages top-down control from the more anterior regions onto the more posterior regions within the inferior frontal circuit, especially when expectancy violations occur and hierarchical relationships between elements are reassessed in terms of tension-relaxation patterns.

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In addition to the inferior frontal circuits, musical syntax, especially beat processing in rhythmic syntax, extensively engages the motor circuit. The motor circuit is involved not only in motor timing (Chauvigné, Gitau, & Brown, 2014), but also in perceptual tasks without any overt movement (Leow & Grahn, 2014). The preferable involvement of the motor circuit in rhythmic syntax is in contrast to linguistic syntax which preferably employs the inferior frontal circuit. As rhythmic syntax builds on the beat which is a temporal representation associated with concrete motor representation, it is uncontroversial that rhythmic syntax more preferably engages the motor circuit for sensory-motor chunk-based control. Moreover, musical syntax seems to utilize the coordination of the motor circuit and the inferior frontal circuit. For example, at least one study investigating syncopation in terms of off-beat tapping showed parallel activations of BA47, the caudate, the pre-SMA/SMA, and the putamen (Mayville et al., 2002). Activations of BA44, the SMA, and the putamen were reported in another study investigating rhythmic sequence processing with the 600 ms interbeat interval (McAuley, Henry, & Tkach, 2012). Moreover, activity in the caudate, BA47, anterior superior temporal gyrus, and the pre-SMA/SMA were modulated by violations of tonal-harmonic syntax (Seger et al., 2013). This study also showed effective connectivity from the IFG to the caudate as well as from the caudate and the putamen to the SMA, indicating that the inferior frontal circuit influences the motor circuit top-down. Thus, in comparison to linguistic syntax, which preferably engages the inferior frontal circuit, musical syntax engages both the inferior frontal circuit and the motor circuit equally, and seems to rely more on the coordination between those two circuits.

### 2.1.3 Basal ganglia and dual control functions

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Finally, the CHC hypothesis suggests that linguistic and musical syntax should engage the dual control functions of the basal ganglia. The neuropsychological studies on Parkinson's disease (PD) and Huntington's disease (HD), which are neurodegenerative diseases affecting the basal ganglia, provide insights into the dual control functions in linguistic and musical syntax. PD and HD lead to abnormal dual control functions as they affect a balanced functioning of the direct and indirect pathway (Graybiel, 2000; Watkins & Jenkinson, 2016).

There is mounting evidence for a crucial role of the basal ganglia in linguistic syntax, particularly again in non-automatic, controlled syntactic processing (for reviews, see Jeon & Friederici, 2015; Kotz, Schwartze, & Schmidt-Kassow, 2009). For example, focal basal ganglia patients show abnormality in controlled syntactic processing (Frisch, Kotz, von Cramon, & Friederici, 2003; Kotz, Frisch, von Cramon, & Friederici, 2003). In a similar vein, both PD and HD patients show impairments in handling sentences with non-canonical syntactic complexity, ambiguity, or embedding (Birba et al., 2017), while they do not show impairments in automatic syntactic processing (Friederici, Kotz, Werheid, Hein, & von Cramon, 2003; Longworth, 2005; Teichmann, Dupoux, Kouider, & Bachoud-Lévi, 2006). As controlled syntactic processing requires inhibition of automatically engaged syntactic representations and selection of alternatives, the abnormal dual control functions in PD and HD patients are reflected in their deficits in controlled syntactic processing. Concerning PD patients, the difference in canonicity (e.g. active vs. passive voice), in general, seems to have no effect on their performance (Grossman, 1999; Terzi, Papapetropoulos, & Kouvelas, 2005). Rather, the presence of alternative interpretations, and thus the need to reorder or alter through balanced selection and inhibition, seems to affect their sentence comprehension (Angwin, Chenery, Copland, Murdoch, & Silburn, 2006; Bocanegra et al., 2015; Friederici, Kotz, et al., 2003; García, Sedeño, et al., 2017). The HD patients' deficits are strongly associated with structural complexity and canonicity of sentences due to their impairments in inhibiting automatically engaged

representations (e.g., canonical interpretation) and applying proper rules to select an alternative representation (e.g., noncanonical interpretation) (García, Bocanegra, et al., 2017; Sambin et al., 2012; Teichmann, Dupoux, Cesaro, & Bachoud-Lévi, 2008; Teichmann et al., 2006, 2005). Those studies provide evidence that linguistic syntax employs the dual control functions of the basal ganglia for controlled syntactic processing.

It is also possible that musical syntax engages the dual control functions of the basal ganglia. For example, as mentioned above, activations of the caudate together with the IFG are reported in connection with rule application and violation (Fujisawa & Cook, 2011; Koelsch et al., 2008, 2002; Kung et al., 2013; Mayville et al., 2002; Musso et al., 2015; Seger et al., 2013; Tillmann et al., 2003). We suggest that those results can be interpreted in terms of the dual control functions because the automatically engaged representations should be inhibited and an alternative should be selected to process expectancy violation. To our knowledge, there is no study which investigates rule-based expectancy violation processing in PD and HD patients. Moreover, there is evidence that rhythmic syntax engages the dual control functions of the basal ganglia. For example, the motor timing deficits of PD patients are more evident when the external cue disappears and the beat should be selected repeatedly internally (Benoit et al., 2014; Tolleson et al., 2015). PD patients and subjects with focal striatal lesion also showed larger variability in spontaneous motor tempo task requiring internal selection of the beat (Rose, Cameron, Lovatt, Grahn, & Annett, 2020; Schwartze, Keller, Patel, & Kotz, 2011). PD patients performed worse than healthy controls in duration or rhythm comparison tasks, i.e., when specific rhythmic representations must be selected and maintained in memory to be compared (Benoit et al., 2014; Biswas, Hegde, Jhunjhunwala, & Pal, 2016; Grahn & Brett, 2009). To maintain the current temporal representation, alternative representations should be suppressed and the current one should be continually selected.

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### **2.1.4 Summary**

In sum, neuroimaging and neuropsychological studies currently available provide data consistent with the CHC hypothesis: Linguistic and musical syntax rely on hierarchical control, but engage this shared mechanism differently. The studies investigating linguistic and musical syntax show activations alongside the abstraction gradient in the frontal cortex and the CBGT circuits. The studies on the temporal abstraction concerning linguistic and musical syntax provided the first evidence for the abstraction gradient of maintained representations. However, the abstraction gradient and the top-down control require more detailed inquiry through experiments which explicitly manipulate the control demand. There is also evidence that linguistic and musical syntax engage the dual control functions of the basal ganglia. The studies reviewed here also showed domain-specific biases of linguistic and musical syntax in engaging the parallel CBGT circuits: Linguistic syntax preferentially engages the inferior frontal circuit to implement abstract rule-based control and relies more on the coordination within the inferior frontal circuit and the motor circuit equally and relies more on the coordination between those two circuits.

#### 2.2 Framing the Coordinated Hierarchical Control hypothesis in light of neural re-use

In the context of current comparative language-music research, Peretz and colleagues (2015) pointed out that neural separability could occur within an overlapping brain region. We agree that specialization for language and music within an overlapping region is possible, and thus it is not possible to take activations in overlapping regions as direct evidence for sharing. However, in line with our CHC hypothesis, we specifically suggest that the differences between language and music reflect different uses of the same set of neurocognitive mechanisms. Concerning the CBGT circuits, it is possible, as Ullman (2006) suggested, that there are further domain-specific subcircuits within the parallel circuits, but their basic operations and function are expected to remain the same. That is, we suggest that no actual overlap in subcircuits is

required for linguistic and musical syntax to share neurocognitive mechanisms. Rather, the basic functions of the circuits are shared by the domain-specific, anatomically segregated subcircuits.

The approach regarding different cognitive capacities such as language and music as different uses of the same set of neurocognitive mechanisms is also in line with an emerging central organizational principle of the brain, namely, neural re-use. This principle is pointed out in research on brain evolution (Anderson, 2010) and brain development (Dehaene & Cohen, 2007). Anderson's "massive redeployment hypothesis" (Anderson, 2010) states that different cognitive capacities are realized by assembling the same neural circuits in specific arrangements, in which each brain region performs a canonical information processing operation ('working') utilized for different capacities ('use'). That is, each circuit and each part of the brain has one fixed 'working', but many different 'uses'. While Anderson's hypothesis mainly refers to neural re-use in the context of evolution (i.e., phylogeny), the other approach taking neural re-use as a basic principle of neural organization into account is the "neural recycling theory" (Dehaene & Cohen, 2007). This theory largely considers neural re-use during development (i.e., ontogeny). Both approaches hold that different cognitive capacities emerge from different uses of the same neural circuits.

In the context of our CHC hypothesis, maintenance through the frontal cortex and selection as well as inhibition through the basal ganglia can be considered as the working of each brain region which can be used differently to process linguistic and musical syntax. Linguistic syntax uses those canonical operations for controlled syntactic processing. This use mostly concentrates on abstract rule-based control implemented in the inferior frontal circuit. Musical syntax uses those canonical operations not only for abstract rule-based control realized by the inferior frontal circuit to process expectancy and expectancy violations, but also for concrete motor control through the motor circuit to maintain temporal representation, especially in the domain of rhythmic syntax. The difference deals with the extent to which linguistic and

musical syntax engage abstract and concrete control. Here, it is important to note that we do not claim that one domain is more abstract than the other. Rather, control processes expressed along the abstraction gradient are differently coordinated to implement linguistic or musical syntax. Whether this domain-specific balance between more abstract or more concrete control emerged in evolution or development still remains to be clarified, but in either case linguistic and musical syntax might emerge from different uses of hierarchical control originally rooted in action control.

### 2.3 Predictions of the Coordinated Hierarchical Control hypothesis

The current hypothesis identifies hierarchical control as a shared neurocognitive mechanism for language and music. It generates predictions about the relationship between neurocognitive mechanisms underlying syntax in language and music that can be tested in future experimental research. We highlight a few below.

First, if syntax in language and music engage hierarchical control, they should show interference and facilitation effects with action syntax, i.e., hierarchical action planning and control. In trained pianists, action planning was influenced by music syntactic knowledge (Bianco, Novembre, Keller, Kim, et al., 2016; Bianco, Novembre, Keller, Scharf, et al., 2016; Sammler, Novembre, Koelsch, & Keller, 2013). A developmental parallel between linguistic syntactic ability and action planning concerning hierarchical combinatorial ability was also demonstrated (Greenfield, 1991). Moreover, impairments in controlled syntactic processing and music syntactic violation processing should co-occur with deficits in hierarchical action planning and control. One study showed action planning deficit in Broca's aphasic patients (Fazio et al., 2009). To our knowledge, however, there is no study directly comparing hierarchical control in linguistic syntax, musical syntax, and action syntax. In particular, the presence of interference effects between these three domains would serve as strong evidence in favor of the CHC hypothesis, while the lack of such interference effects would argue against it.

Second, the abstraction gradient of the CBGT circuits should be tested more explicitly in the future research on linguistic and musical syntax. For example, Koechlin and Jubault (2006) tested hierarchical control in the action domain by using an event-related functional magnetic resonance imaging (fMRI) design and showed the abstraction gradient within Broca's region for action control. In this experiment, the execution of learned motor chunks was associated with the activation of BA44, while the execution of motor responses based on contextual cues related to the activation of BA45. Moreover, the same experiment showed that phasic activations in initiation and termination of learned motor chunks were found in BA44, while phasic activations in initiation and termination of contextually controlled action execution were detected in BA45. The abstraction gradient associated with linguistic and musical syntax can be tested in a similar way. That is, in the experiments investigating linguistic and musical syntax, phasic activations at the larger chunk boundary should be detected in the more anterior region, while those at the smaller chunk boundary should be detected in the more posterior region. The lack of such an anterior-posterior activation pattern would falsify the CHC hypothesis.

Third, if linguistic and musical syntax engage top-down control, there should be some information flow from the anterior to posterior regions via the basal ganglia depending on the control demand. One possibility to investigate the top-down causal influence is the analysis of effective connectivity (e.g., through structural equation and dynamic causal modeling) (Friston, Harrison, & Penny, 2003; Stephan et al., 2010). For example, Koechlin and colleagues (2003) not only showed the abstraction gradient in action control, but also provided evidence for the top-down control from anterior to posterior frontal regions by analyzing effective connectivity. As we reviewed in Section 2.1, Seger and colleagues (2013) also applied effective connectivity analysis in their fMRI study on tonal-harmonic syntax. The importance of effective connectivity analysis for investigating the relationship between linguistic and musical syntax was already pointed out by Grahn (2012). More research along these lines is required to support or reject

the top-down control suggested by the CHC hypothesis. In the studies investigating linguistic and musical syntax, the detection of the anterior-to-posterior information flow through effective connectivity analysis would provide further evidence for the CHC hypothesis, while the lack of such a flow, or the inverse information flow, would falsify it.

### 3 Reassessing comparative research on linguistic and musical syntax

In line with the "resource sharing framework" (Patel, 2003), a number of behavioral, neuroimaging, and neuropsychological studies provided evidence for shared neural resources for linguistic and musical syntax in the past decades (Table 2). How do the shared neural resources revealed by those previous studies relate to hierarchical control? In Section 3.1, we suggest that the shared neural resources can be explained in terms of the resources required for the maintenance function and the dual control functions. Our discussion centers on the interference and facilitation effects, which result from interaction between linguistic and musical syntax. Especially, interference effects provide strong evidence for shared neural resources (Sleve & Okada, 2015). Moreover, although comparative language-music research has reached a general consensus on the existence of the shared neural resources, there are various proposals with a view to explaining their nature (Fedorenko & Blank, 2020; Fedorenko & Varley, 2016; Fitch & Martins, 2014; Jeon, 2014; Kljajevic, 2010; Kotz et al., 2009; Sleve & Okada, 2015). In Section 3.2 and 3.3, we discuss the relationship of our CHC hypothesis to those previous proposals to explore the way to integrate the CHC hypothesis into a larger framework.

Table 2 Studies investigating shared neural resources for linguistic and musical syntax. The studies were searched in PubMed and Web of Science with "language music (syntax OR syntactic)" as a search criterion (Date: January 10th, 2021). In addition, we conducted a search in PsyArXiv with "title: (language AND music) (syntax OR syntactic)" as a search criterion to include relevant studies not yet peer-reviewed. After manual inspection, we excluded the studies which did not explicitly provide evidence for the shared neural resources for linguistic and musical syntax: studies investigated musical training effect, lexical decision task, and visual timing were excluded. Thus, the list is not fully representative of the literature. Descriptions of the "Methods" column: Parallel = parallel presentation of linguistic and musical stimuli; Priming = musical stimulus precedes linguistic stimulus; if none of them is stated, it deals with comparison between linguistic and musical condition or between-group comparison. Abbreviations: early left anterior negativity (ELAN); early right anterior negativity (ERAN); left anterior negativity (LAN) object-extracted relative clause (OR); Parkinson's disease (PD); sequences (seq.); specific language impairment (SLI); subject-extracted relative-clause (SR)

Authors (Year)	Methods	Language Language	Music	Effects	Results			
Tonal-harmonic syntax								
Carrus et al. (2011)	EEG (Parallel)	Sentence with & without syntactic violation	Ending of seq. with & without irregular chord	Interference	Interaction between linguistic and musical syntactic violation processing in the late delta-theta band activity			
Chiang et al. (2018)  Musicians	fMRI	Active and passive voice sentences	Ascending triads in root and second-inversion position	-	Overlap between language and music in the left IFG (BA44), the middle frontal gyrus (BA6), the medial frontal / cingulate gyri (BA6, BA32), and the bilateral posterior parietal lobe (BA7, BA40)			
De Leeuw et al. (2019)	EEG	Grammatical & ungrammatical sentence	Seq. with and without tonally distant chord	-	No statistical difference in P600			
Fedorenko et al. (2009)	Behavioral (Parallel)	Center-embedded SR & OR	Seq. with & without out-of-key tone	Interference	Influence of out-of-key tone processing on OR processing			
Fiveash & Pammer (2014)	Behavioral (Parallel)	Center-embedded OR & word list	Seq. with & without out-of-key chord	Interference	Influence of out-of key chord processing on memory task, i.e., sentence reproduction			
Fiveash et al. (2018)	Behavioral (Parallel)	Center-embedded OR & word list	Scrambled, regular (i.e., non-scrambled), & regular timbre-modified melody	Interference	Influence of scrambled melody on memory task, i.e., word list and sentence reproduction; Influence of			

					non-scrambled melody on sentence reproduction
Jentschke et al. (2008) SLI children & controls	EEG	-	Ending of seq. with & without irregular chord	-	No ERAN in SLI children
Koelsch et al. (2005) & Steinbeis & Koelsch (2008)	EEG (Parallel)	Sentence with & without agreement violation	Ending of seq. with & without irregular chord	Interference	Interaction between LAN and ERAN
Kunert et al. (2015)	fMRI (Parallel)	Center-embedded SR & OR	Seq. with & without out-of-key tone	Interference	Language-music interaction in Broca's region (BA44 & 45)
Kunert et al. (2016)	Behavioral (Parallel)	Regular & garden-path sentence; center-embedded SR & OR	Seq. with modulation ending in the 1 <sup>st</sup> or 2 <sup>nd</sup> key	-	Influence of garden-path on musical closure rating (1 <sup>st</sup> key); Influence of OR processing on musical closure rating
Patel et al. (1998)	EEG	Grammatical, garden- path & ungrammatical sentence	Seq. with and without more or less tonally distant chord	-	No statistical difference in P600
Patel et al. (2008)  Broca's aphasia & controls	Behavioral	Thematic role assignment (five levels of syntactic complexity)	Out-of-key chord & harmonic priming	-	In the patients: Deficit in thematic role assignment (more pronounced in complex conditions); Deficit in detecting harmonic anomalies & no harmonic priming effect
Sammler et al. (2013)  Patients with epilepsy	Intracranial EEG	Sentence with & without phrase structure violation	Seq. with & without out-of-key chord	-	Overlapping source for ELAN and ERAN in the superior temporal lobe
Sleve et al. (2009)	Behavioral (Parallel)	Regular & garden-path sentence	Seq. with & without out-of-key chord	Interference	Influence of out-of-key chord processing on garden-path sentence processing
Sun et al. (2018)	EEG	Sentences with & without agreement	Melody with & without music	-	Neither LAN nor ERAN in the subjects with Amusia
Amusics & controls		violation	syntactic violation		

Van de Cavey &	Behavioral	Ambiguous relative	Pitch seq. with ABA	-	Structural priming effect of pitch				
Hartsuiker (2016)	(Priming)	clause (ABA vs. ABB)	vs. ABB structure		sequence on relative clause				
		Di-	41		processing				
Rhythmic syntax									
Bedoin et al. (2016)	Behavioral	Sentence with & without	Seq. with regular (i.e.,	Facilitation	Improvement of grammaticality				
	(Priming)	agreement violation	metrical) rhythm and		judgement in all groups through				
SLI children & controls			environmental sound		regular priming				
Canette et al. (2020)	EEG	Sentence with & without	Seq. with regular (i.e.,	Facilitation	Larger P600 through regular				
	(Priming)	agreement violation	metrical) and irregular		priming				
(replication)			rhythm						
Chern et al. (2018)	Behavioral	Sentence with & without	Seq. with regular (i.e.,	Facilitation	Improvement of grammaticality				
	(Priming)	agreement violation	metrical) and irregular		judgement through regular priming				
Children			rhythm						
Gordon et al. (2015)	Behavioral	Structured Photographic	Seq. with simple and	-	Correlation between language				
		Expressive Language	complex rhythm		ability and rhythm discrimination				
Children		Test			ability				
Hilton & Goldwater	Behavioral	Center-embedded SR &	Seq. with congruent &	Interference	Worse sentence comprehension				
(2020)	(Parallel)	OR	incongruent meter		performance in meter-syntax				
					incongruent condition; More tapping				
					variability in meter-syntax				
					incongruent condition				
Kotz & Guenther (2015)	EEG	Sentence with & without	March (congruent) &	Facilitation	Recovery of P600 in March priming				
	(Priming)	phrase structure violation	Waltz (incongruent)		condition				
One PD patient			rhythm						
Lee et al. (2020)	Behavioral	Center-embedded SR &	Seq. with simple	-	Correlation between sentence				
		OR	rhythm		processing ability and rhythm				
Children					discrimination ability				
Przybylski et al. (2013)	Behavioral	Sentence with & without	Seq. with regular (i.e.,	Facilitation	Improvement of grammaticality				
	(Priming)	agreement violation	metrical) and irregular		judgement in all groups through				
SLI children & controls			rhythm		regular priming				

#### 3.1 Shared resources for the maintenance function and the dual control functions

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The interference effect between controlled syntactic processing and musical syntactic violation processing is most striking from a perspective of the CHC hypothesis as they both likely engage the maintenance function as well as the dual control functions. For example, a number of studies showed that processing sentences with a center-embedded relative clause interfere with musical syntactic violation processing (Fedorenko et al., 2009; Fiveash & Pammer, 2014; Hilton & Goldwater, 2020; Kunert et al., 2015). Processing sentences with center-embedding requires high control demand as the representation of the main clause should be inhibited and maintained during processing the embedded clause. In comparison to sentences with the subject-extracted relative clause (RC) (e.g., "[The researcher [that met the professor]<sub>SUBJECT-EXTRACTED RC</sub> drank tea instead of coffee]."), sentences with the object-extracted relative clause (e.g., "[The researcher [that the professor met]OBJECT-EXTRACTED RC drank tea instead of coffee.]") are considered to be more demanding. Processing garden-path sentences also interferes with musical syntactic violation processing (Slevc et al., 2009). Garden-path sentences (e.g., "The horse raced past the barn fell.") also demand more resources, especially those of the dual control functions, as the established interpretation should be inhibited and an alternative interpretation should be selected.

Our suggestion that controlled syntactic processing and musical syntactic violation processing shares neural resources for the maintenance and the dual control functions is in line with the finding that processing out-of-key chords elicits a P600 which does not statistically differ from that elicited by processing garden-path or ungrammatical sentences (De Leeuw et al., 2019; Patel et al., 1998). The P600 is an ERP component which is associated with late controlled syntactic processing in language and was suggested to have its origin – at least partially – in the basal ganglia as P600 is reduced or absent in focal basal ganglia patients as well as PD patients (Friederici & Kotz, 2003). People with Broca's aphasia (with lesions to frontal, temporal, and/or parietal sites) also show a reduced or absent P600 (Kaan, 2007). Thus,

the P600 seems to emerge from a complex interplay between cortical regions and the basal ganglia, in which the frontal cortex contribute with the maintenance function to controlled syntactic processing and the basal ganglia with the dual control functions.

Moreover, we suggest that facilitation effects of musical syntax onto controlled syntactic processing in part deals with the relief of resources required for the dual control functions. The P600 of a PD patient showed recovery when sentences were processed after rhythm priming with congruent metrical structure (Kotz & Gunter, 2015). In healthy adults, too, a larger P600 was observed when sentences were processed after regular rhythm priming (Canette et al., 2020). Not only rhythm priming, but also structural priming with pitch sequences facilitates ambiguous relative clause processing (Van de Cavey & Hartsuiker, 2016). In light of our CHC hypothesis, those results can be interpreted as follows: because regular musical sequences do not demand the dual control functions, resources can be fully claimed by controlled syntactic processing. However, those facilitation effects cannot be fully explained in terms of the shared dual control functions alone. There should be a complementary mechanism underlying the facilitation effects, to which we will come back in Section 3.3.

Facilitated processing for aligned musical and linguistic structures is also observed in morpho-syntactic processing in both children with and without developmental language disorder (called "specific language impairment" (SLI) by the authors) (Bedoin et al., 2016; Chern et al., 2018; Przybylski et al., 2013). Although the aetiology of developmental language disorder is complex, one systematic review article discussing neuroimaging studies about childhood language disorders found that several studies consistently identified atypical brain structures in the inferior frontal gyrus (especially in the pars triangularis (BA45)), the caudate, and the posterior superior temporal gyrus (STG) (Mayes, Reilly, & Morgan, 2015). Less accurate tapping performance of the SLI children (Corriveau & Goswami, 2009; Cumming, Wilson, Leong, Colling, & Goswami, 2015) also indicates abnormal functions of the brain

regions which are crucial to rhythmic syntax. Therefore, we think it's worth discussing developmental language disorder in light of our current hypothesis.

As a P600 was consistently reported to be present in SLI children (Fonteneau & van der Lely, 2008; Sabisch, Hahne, Glass, von Suchodoletz, & Friederici, 2009), abnormal syntactic processing seems not to result from abnormal dual control functions. Rather, SLI children show impairments in syntactic processing at an early automatic processing stage as observed in the absence of the early left anterior negativity (ELAN) (Fonteneau & van der Lely, 2008; Sabisch et al., 2009). In addition, early right anterior negativity (ERAN) reflecting musical syntax at an early automatic processing stage is also absent in SLI children (Jentschke et al., 2008). Thus, syntactic impairments in SLI children relate to this early automatic syntactic processing which does not require hierarchical control. At first glance, this seems to oppose our hypothesis.

However, if overlearned rule representations are not available in SLI children, they indeed might require active maintenance in frontal cortical regions. This interpretation is in line with the idea that syntactic impairments of SLI children come from their disability to learn rule representations through procedural learning via the CBGT circuits (Krishnan, Watkins, & Bishop, 2016; Ullman & Pierpont, 2005) and from abnormal short-term storage (Gillam, Montgomery, Gillam, & Evans, 2017; Montgomery, Gillam, & Evans, 2016). In addition, ERAN amplitude was correlated with children's maintenance capacity (Jentschke et al., 2008). This all points to a limitation of maintenance resources as a possible reason for processing difficulties of SLI children in processing linguistic and musical syntax.

In case of processing structural violations, more resources for the maintenance function are required because processing based on overlearned rule representations is no longer possible and incoming information should be actively maintained. For example, the amplitude of the left anterior negativity (LAN) which reflects agreement violation processing was smaller if the critical word was presented with an irregular chord and the amplitude of ERAN was also smaller if the critical chord was presented with a syntactically unexpected word (Koelsch,

Gunter, et al., 2005; Steinbeis & Koelsch, 2008). Linguistic and musical syntactic violation processing also interferes with each other in the late delta-theta band activity (Carrus et al., 2011). The result that both word list and sentence reproduction was influenced by scrambled melody (Fiveash et al., 2018) could be also explained such that processing of scrambled melodies requires active maintenance due to absence of any overlearned rule representations.

#### 3.2 Beyond domain-specificity vs. -generality: Specialization of executive function?

Our CHC hypothesis is in line with the view that working memory underlies the sharing of neural resources for linguistic and musical syntax (Fitch & Martins, 2014; Kljajevic, 2010). What is referred to by those authors as working memory can be explained in terms of maintenance through the frontal cortex together with selection and inhibition through the basal ganglia. However, we additionally suggest that maintenance and dual control functions show specialization to implement linguistic and musical syntax. The CHC hypothesis also extends the previous claim that the shared resource for linguistic and musical syntax processing is cognitive control implemented in the frontal cortex (Jeon, 2014; Slevc & Okada, 2015) by explicitly stating how hierarchical control is engaged differently in those two domains. Thus, in general terms, we suggest that linguistic and musical syntax employ specialized forms of executive function.

The CHC hypothesis focuses on specialization in terms of different coordination of more abstract temporally extended control and more concrete motor control. Of course, this is not the only way to yield a specialized form of executive function. For example, it is also possible that the functional specialization of a brain region is determined by the large-scale network to which the brain region belongs (Fedorenko & Blank, 2020; Fedorenko & Thompson-Schill, 2014; Peretz et al., 2015). While this network approach tends to put more emphasis on the parallel existence as well as the separability of the domain-specific network for idiosyncratic computation and the domain-general network for cognitive control, we focus

on the possible continuity between those two networks. Fedorenko (2014) and Fedorenko and Varley (2016) emphasized the domain specificity of the language-selective network, while leaving open the possibility that the language-selective network emerges in the course of the development. Thus, our suggestion that linguistic and musical syntax employ specialized forms of executive function do not contradict the network approach as such, but only one version of it.

For example, although BA44 was repeatedly put forward as a candidate region where linguistic and musical syntax processing overlap, there is also evidence that language and music preferably recruit different parts of left BA44 which also show different connectivity patterns (Clos, Amunts, Laird, Fox, & Eickhoff, 2013). Given maintenance as a canonical neural process of the frontal cortex, differences between language and music within BA44 can be regarded as a specialization of the shared maintenance function. To establish structural relations between non-adjacent elements, a buffer-like function is necessary for both language and music (Fitch & Martins, 2014). This buffer-like function in BA44 differs from one establishing relations between temporally distant elements, associated with the inferior frontal sulcus (Makuuchi et al., 2009), indicating the different types of the maintenance function within the frontal cortex. That is, different parts of BA44 are embedded in distinct large-scale networks to implement idiosyncratic computations, but the working of BA44 in terms of the maintenance function remain constant.

Another study showed that there are language-selective and domain-general parts within Broca's region: the language-selective part was found especially in BA45 (Fedorenko, Duncan, & Kanwisher, 2012). This study also identified a subpart of BA44 that was more active during language processing than during other conditions, but even this subpart showed significant activation in challenging verbal working memory and stroop tasks. This was not witnessed in the language-selective part of BA45. This is also in line with the finding that BA45 activation during non-canonical sentence processing is language-specific and not due to articulatory

rehearsal (Rogalsky, 2008). Based on these findings suggesting some form of language-specificity in BA45 within Broca's region, Matchin (2018) argued that BA45 together with the arcuate fasciculus implements a syntactic memory retrieval mechanism, which results from a retuning of working memory mechanism implemented in the frontal cortex. He suggested that the language-specificity within BA45 emerges as a consequence of the domain-specific representations stored in the left posterior temporal region which are retrieved via the arcuate fasciculus. Again, the maintenance function remains the same, but a domain-specific representation retrieved from the long-term memory storage is maintained. Thus, rare activation of BA45 by musical syntax (**Box 1**) could result from differences in long-term memory representation.

A further relevant consideration is the role of the dorsolateral prefrontal cortex (BA9 and 46) and the executive circuit (**Figure 1**). The dorsolateral prefrontal cortex and the executive circuit are consistently implicated in executive function (Niendam et al., 2012) and are constituents of hierarchical control (Badre & Nee, 2018). However, discussions of syntax are often limited to the IFG and the inferior frontal circuit. This is because linguistic and musical syntax are mainly investigated within one task-set (e.g., sentence processing or short musical sequence processing). As Rouault and Koechlin (2018) pointed out, hierarchical control within a task-set takes place within the IFG and the premotor cortex, while hierarchical control concerning the anterior lateral prefrontal cortex (including BA9 and 46) and the polar lateral prefrontal cortex deals with temporal control over task-sets. They suggested that the former corresponds to sentence generation and linguistic syntax, while the latter conforms to discourse generation. In line with this claim, the dorsolateral prefrontal cortex is associated with discourse processing rather than sentence processing (Coelho, Lê, Mozeiko, Krueger, & Grafman, 2012; Sirigu et al., 1998). Hierarchical control within overlearned task-set in action domain also showed activation in Broca's region (Koechlin & Jubault, 2006). Thus, hierarchical control

implemented in the IFG and the inferior frontal circuit can be regarded as specialization of executive function in terms of different task-sets.

In sum, the CHC hypothesis is one part of a more general suggestion that linguistic and musical syntax employ specialized forms of executive function. It goes beyond the dichotomy of domain-generality vs. -specificity by placing language, music, and executive function on a continuum. While the CHC hypothesis explains the relationship between linguistic and musical syntax in terms of different coordination of control processes on the abstraction gradient, the network approach adds to the further possibility that the specialization of hierarchical control for each domain could additionally come from the network in which the mechanism is embedded. Thus, together, the CHC hypothesis and the network approach provide a more coherent picture of the relationship between linguistic and musical syntax.

#### 3.3 Relationship between hierarchical control and prediction

Prediction is another candidate shared mechanism underlying syntax in language and music (Heard & Lee, 2020; Koelsch, Vuust, & Friston, 2019; Kotz et al., 2009; Patel & Morgan, 2017; Rohrmeier & Koelsch, 2012). For example, Kotz and colleagues (2009) suggested that linguistic syntax engages prediction which also underlies processing of temporally predictable cues and put emphasis on the interplay between the pre-SMA and the basal ganglia for temporal coordination in linguistic syntactic processing. This proposal appears to conflict with our CHC hypothesis, as it emphasizes the role of the inferior frontal circuit for linguistic syntax. However, the relationship between hierarchical control and prediction is rather complementary than contradictory. While our CHC hypothesis focused on hierarchically organized control processes, hierarchically organized prediction is another important component of cognitive control (Badre & Nee, 2018; Slevc & Okada, 2015).

Although research on the relationship between hierarchical control and prediction is still in its infancy, the "Hierarchical Reinforcement Learning" (HRL) model (Badre & Frank, 2012;

Frank & Badre, 2012) and the "Hierarchical Error Representation" (HER) model (Alexander & Brown, 2015, 2018) provide the possibility to disentangle this relationship. The HRL model integrates reward prediction of the basal ganglia into the dual control function of hierarchical control: through reward prediction error, the model learns to select and inhibit appropriate response given current contexts maintained in the frontal cortex. The HER model keeps some components of hierarchical control such as the maintenance and the dual control functions as well as the hierarchy of abstraction, but implements top-down control and bottom-up feedback processing in terms of prediction. In this model, prediction and prediction error are hypothesized to be processed by the hierarchical interaction between the lateral and medial frontal regions. Thus, in any case, hierarchical control and prediction are tightly interwoven.

A recent meta-analysis of predictive processing in language, music, and action reports consistent activations in a widely distributed brain network including the prefrontal cortex, temporo-parietal junction, anterior insula, the basal ganglia, the thalamus, and the cerebellum (Siman-Tov et al., 2019). That is, the prefrontal cortex and the basal ganglia discussed in the context of hierarchical control play a part in the prediction network. This is uncontroversial given the tight relationship between hierarchical control and prediction. Thus, the central question is how prediction is used by linguistic and musical syntax in interaction with hierarchical control and not whether the shared mechanism is hierarchical control or prediction.

We, thus, suggest that the facilitation effect of regular cues onto various motor and cognitive domains is one good candidate phenomenon to investigate the interplay between hierarchical control and prediction. For example, while PD patients show deficits in processing musical rhythm, a number of studies showed that musical rhythm helps them to improve their motor control (for reviews, see, e.g., Koshimori & Thaut, 2018; Nombela, Hughes, Owen, & Grahn, 2013; C. Thaut & Stephan, 2019). Such positive effects through musical rhythm are possible either through facilitation of the basal ganglia activities (te Woerd, Oostenveld, Bloem, de Lange, & Praamstra, 2015) or supportive compensatory mechanisms recruiting frontal and

parietal cortical regions associated with executive function together with the cerebellum, auditory- as well as motor-related cortical regions, and the planum temporale (Braunlich et al., 2019; Vikene, Skeie, & Specht, 2019a, 2019b). Those regions show considerable overlap with the prediction network suggested by Siman-Tov and colleagues (2019). Moreover, one study showed an improvement of executive function in HD patients after rhythm exercise (Metzler-Baddeley et al., 2014). Thus, it is possible that external regular cues not only unburden, but also actively assist the working of executive function via prediction. Similarly, the facilitation effect of regular musical sequences onto linguistic syntactic processing (Bedoin et al., 2016; Canette et al., 2020; Chern et al., 2018; Kotz & Gunter, 2015; Przybylski et al., 2013) could be supported by prediction, possibly via the frontal aslant tract connecting the pre-SMA/SMA with Broca's region (Heard & Lee, 2020).

In sum, hierarchical control and prediction are central constituents of cognitive control and work in tandem to yield behavioral flexibility. Thus, research on the relationship between linguistic and musical syntax from a perspective of cognitive control should investigate both mechanisms as candidates for shared neurocognitive mechanisms. However, as we suggested throughout the paper, it is possible that the same mechanisms are utilized differently by linguistic and musical syntax, which could also be the case for prediction and the interplay between the two mechanisms.

# 4 Conclusions and future perspectives

To conclude, we have claimed that hierarchical control is a shared neurocognitive mechanism underlying syntax in language and music. Brain bases of hierarchical control include 1) functional organization of frontal cortex to maintain more abstract representations in the more anterior regions and more concrete representations in the more posterior regions, 2) dual control functions (selection and inhibition) of the basal ganglia, and 3) top-down influence from abstract temporally extended process onto concrete motor process via the CBGT circuits. Our

Coordinated Hierarchical Control (CHC) hypothesis suggests that language and music rely on hierarchical control realized by the CBGT circuits, but engage this shared mechanism differently depending on the current control demand, i.e., more abstract temporally extended control or more concrete motor control. Differently abstract control processes expressed along the abstraction gradient are coordinated to implement linguistic or musical syntax in their own ways. More generally, the CHC hypothesis belongs to a framework regarding linguistic and musical syntax as different uses of the same mechanism. We have shown that the CHC hypothesis generates several novel testable predictions that we hope will be tackled in future work.

Our CHC hypothesis extends the previous resource sharing framework (Patel, 2003, 2013) in important ways. First, and most importantly, our hypothesis highlights the oftneglected fact that the shared processes are utilized differently to implement linguistic and
musical syntax depending on the current control demand. The sharing and non-sharing of
language and music cannot be explained in a strict black and white manner. Second, our
hypothesis deals with the question of what the shared neurocognitive mechanism underlying
syntax in language and music is. Comparative research on language and music requires such a
hypothesis accounting for a mechanistic explanation (see also Slevc & Okada, 2015 for a
similar claim). Third, our hypothesis integrates rhythmic syntax and the basal ganglia, avoiding
a purely Western pitch-centric view of musical syntax as well as cortico-centric view of
neurocognitive mechanisms underlying syntax.

In the current paper, we focused on the interplay between the frontal cortex and the basal ganglia. However, to gain a more complete picture of syntax in language and music, the discussion about domain-specific long-term memory representations in the temporal regions should also be integrated. Especially, the relationship between linguistic and musical syntax in terms of the fronto-temporal network via the left and right arcuate fasciculus respectively is to be clarified (Friederici, 2019). While the left posterior temporal region is indicated in structure

building of linguistic syntax (Matchin & Hickok, 2020), there is evidence that the right posterior temporal region is rather crucial for structure building in musical syntax (Martins et al., 2020). As the right IFG is also organized according to the abstraction gradient (Hartwigsen, Neef, Camilleri, Margulies, & Eickhoff, 2019) and is also involved in hierarchical control (Koechlin & Jubault, 2006), the main difference between linguistic and musical syntax regarding the left and right arcuate fasciculus may result from different long-term memory representations to be retrieved. Moreover, the left anterior superior temporal gyrus is one important neural correlate of musical syntax (Koelsch, 2012). As one study on linguistic phrase structure processing activated the left anterior STG together with the putamen and the left frontal operculum (Friederici, Rüschemeyer, Hahne, & Fiebach, 2003), future research should also consider the interplay between the putamen and the anterior STG.

It is also worth noting that our CHC hypothesis can be integrated with other frameworks putting more emphasis on sequencing (ordering and timing) as common denominator of speech, language, music, and action. For example, Kotz and Schwartze (2010) suggested that the pre-SMA/SMA, the basal ganglia, and the cerebellum coordinate temporal structure as well as synchronize internal and external attention. As the cerebellum is also implicated in executive function (D'Mello, Gabrieli, & Nee, 2020; Marvel et al., 2019) and engaged by linguistic syntax and musical syntax (Adamaszek & Kirkby, 2016; Kotz et al., 2009), its role should be further specified in light of our CHC hypothesis. Moreover, because P600 is elicited only if participants internally attend to structural features of music through tasks (D. J. Lee, Jung, & Loui, 2019), the dual control functions of the basal ganglia could relate to internally controlled attention as suggested by Brown and Marsden (1988). Jung and colleagues (2015) suggested that there are shared attentional resources involved in the processing of garden-path sentences and musical rhythm. In this context, entrainment is a further mechanism whose relation to hierarchical control needs clarification in the future research. Entrainment of internal and external attention was suggested to play a role in language processing (Rothermich, Schmidt-Kassow, & Kotz,

2012; Schmidt-Kassow & Kotz, 2008). Neural entrainment was suggested to be a neurocognitive mechanism underlying linguistic and musical syntax (e.g., Baltzell, Srinivasan, & Richards, 2019; Ding, Melloni, Zhang, Tian, & Poeppel, 2016).

Finally, although our CHC hypothesis focused on the relationship between linguistic and musical syntax, it can be elaborated to include further domains such as prosody (i.e., pitch and rhythm in speech). For example, Kotz and colleagues (2018) emphasized the tight relationship between rhythm in speech and music. One recent review also suggests that temporal structure (rhythm in particular) processing influences speech processing of non-fluent aphasia and proposes that rhythm processing as the function of temporal prediction is a shared component underlying music and speech (Shi & Zhang, 2020). Moreover, processing of linguistic meter and syntax was suggested to interact in P600 (Schmidt-Kassow & Kotz, 2009). Thus, our discussion on the interplay between hierarchical control and prediction could be extended to include the relationship between rhythm in speech and music. Further, the pre-SMA/SMA is linked to Broca's region via the frontal aslant tract and could mediate phonological, prosodic, and syntactic processing (Hertrich et al., 2016). In this context, as the right anterior negativity in prosodic processing was also absent in the SLI children (Sabisch et al., 2009), the role of prosody in relation to the maintenance function needs further clarification. Future research on hierarchical control together with prediction could provide a more complete picture on how language, speech, and music relate to each other in the brain and cognition.

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