



The Influence of Musical Activities on Cognitive Control Mechanisms

Overview and empirical findings

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This article provides an overview of the ways music therapy may contribute to the improvement of cognitive control mechanisms, which play a central role in managing our goal-directed behaviors. First, we introduce the cognitive control model of Cohen (2017) and we summarize the main findings of the literature about the near and far transfer effects of music therapy. The integration of these two theoretical frameworks will allow us to describe the associations between higher-level cognitive control functions and music processing. In the second part of this paper, we present the preliminary findings of our recent study. We examined the relationship between formal regular music training and cognitive control in young adults by focusing on working memory updating and cognitive flexibility. We used the N-back paradigm with manipulations in task complexity and modality (visual (letters and shapes); auditory (pitches and timbres)) to examine whether long-term musical experiences affect working memory updating and cognitive flexibility. Our results revealed that the musicians were more accurate in working memory updating than their non-musician peers. Further, the musicians' performance was significantly better in the pitch N-back task than in the timbre N-back. In contrast to accuracy, the groups did not differ in reaction time. Our first results support the notion that musical training may promote the development of certain cognitive control skills, but further research is needed to better understand this relationship.

Keywords: musical activity, cognitive control, cognitive flexibility, working memory updating

Introduction

Cognitive control is a complex mechanism, which underlies our ability to pursue goal-directed behaviours (Cohen, 2017). It plays a central role in educational success, work, and everyday life activities across the lifespan (Rhoades et al., 2009; Brock et al., 2009; Jacobson et al., 2011; Diamond & Fiske, 2013). Cognitive control intervention may be an important part of habilitation and rehabilitation processes. Several disorders have been shown to involve deficits in cognitive control functions: e.g., autism spectrum disorder (de



Vries et al., 2015; Solomon et al., 2016; Hogeveen et al., 2017), attention deficit hyperactivity disorder (de Zeeuw et al., 2012; Jarrett et al., 2016) and specific language impairment (Marton et al., 2014; Marton et al., 2016) among others.

Individual differences in cognitive control can be explained by the *cognitive flexibility* theory (Botwinick et al., 2001). In this widely accepted framework cognitive flexibility indicates the adaptability of the cognitive system to immediate changes in information that is being processed during task performance (Botwinick et al., 2001). A number of studies investigated the factors that contribute to cognitive flexibility (aging, socioeconomic status, occupation, life experience), among these are *musical activities* that have been in the focus of a growing number of studies in recent years (Thaut, 2010; Zuk et al., 2014; Siepsiak & Krejtz, 2016; Jaschke et al., 2018; Porflitt & Rosas, 2020; Chen et al., 2021).

The aim of this article is to demonstrate how regular musical activities can advance cognitive development by facilitating cognitive flexibility. First, we present an overview of the existing research on this topic, explain the underlying theoretical connections, address some of the main controversies in literature, and suggest potential directions for further research based on the results of our preliminary study.

Cognitive control and cognitive flexibility

Cognitive control is a complex construct (Cohen, 2017), which refers to the ability to pursue goal-directed behaviours instead of more habitual or immediately more compelling behaviours (Egner & Hirsch, 2005), allowing information processing and behaviour to vary adaptively over time with changes in task objectives. It supports the maintenance of the activation level of newly picked-up information and the retrieval of relevant contents from memory, as well as the suppression of irrelevant information and/ or behavioural responses (Dudukovic & Kuhl, 2017). More efficient cognitive control may be reflected by faster interpretation of information (shorter reaction times) (Marton et al., 2017). Although the terms cognitive control and executive functions are often used as synonyms in the literature, behaviours associated with the cognitive control account are more clearly defined and closely linked to specific neurobiological structures and processes (Marton, 2016).

The most prominent features of the cognitive control model are *flexibility* and *adaptation*: two mechanisms that play a critical role in information processing and learning. The adaptability of the cognitive control system can be illustrated by the *working memory updating process*. There are several frameworks and experimental paradigms associated with working memory updating, however, in the current study we are using the interference model by Oberauer to interpret updating performance, which involves rapidly refreshing working memory representations to focus on information relevant to the task goal (Oberauer, 2002). Successful updating requires two conceptually different mechanisms: stability and flexibility. In order to accurately recognize target items, strong, stable working memory representations of content-context

bindings are needed, whereas flexibility is required to refresh the previous representations of content-context bindings in order to process new incoming information efficiently (Wadhera et al., 2018).

Cognitive flexibility is reflected by the cognitive system's responses to different contextual changes. (Cohen, 2017) For example, if certain items, conditions, or tasks are frequently repeated, our performance becomes faster and more accurate. Thus, performance becomes more automatized with practice because the cognitive system adapts to the repeated items and processes. In contrast, if the task becomes more complex, or more difficult, that is, if the conditions change, then we become slower and less accurate because the task requires more top-down control from our cognitive system.

According to the cognitive control account (Cohen, 2017), *controlled and automatic processes* create a continuum; the more cognitive control is needed, the less automatic the behaviour becomes. Automatization also means that more capacity can be freed up for other cognitive operations (Botvinick et al., 2001). However, the same behaviour may be more automatic in one situation and more controlled in another one, depending on the person's experience with a given task (learning effect) and on the contextual conditions, such as task features (e.g., set size) or interfering processes in a given situation (Botvinick & Cohen, 2014; Cohen, 2017). For example, in a memory task, the more items we must remember, the more control is needed. If there is interference among the items to-be-remembered (e.g., they are phonologically similar), then even more control may be required. Thus, performance on cognitive tasks depends on numerous factors including individual differences in control functions, task conditions, and familiarity with the task:

A number of these cognitive control phenomena can be observed directly in musical activities:

1. The execution of controlled tasks is slower than that of automatic ones. (Example: while practising a new piece of music we need more control, but later it becomes automatic.)
2. The controlled processes may be competing and interfering with each other and with some more automatic processes while playing music. (Example: while playing music one needs to look at the notes -even preview some beats-, listen to the other musicians, keep the tempo, and the right loudness, etc.)
3. The controlled processes may rely on a central, limited capacity system (Example: one's working memory capacity limits the activities performed in parallel, like it is difficult to play drums and sing at the same time) (Shiffrin & Schneider, 1977; Schneider & Shiffrin, 1977).

As these examples show, musical activities provide a rich set of opportunities to train cognitive control functions. In the next section we are introducing music's developmental mechanism of action and clarifying some important terms used in our study.

Music as a driving force of development

Playing, listening to and creating music involve practically every cognitive function (Zatorre & Salimpoor, 2013; Zuk et al., 2014). In addition, its emotional, psychological effects make music a good motivator in any pedagogical, developmental, and therapeutical situation. Musical activities are both social and enjoyable interventions with positive effects on functional and structural brain plasticity and may enhance general cognitive and perceptual motor function (Cooper, 2019). Music's widely known *transfer effect* can be explained by the greatly distributed brain areas involved in music performance that support many other cognitive and perceptual-motor skills (Mansouri et al., 2017). Transfer of learning takes place when skills learned in one particular area either generalize to new areas or increase general cognitive abilities (Brookes et al., 2011). There are two broad categories of transfer to distinguish: near transfer (the transfer of skills within the same domain) and far transfer (the transfer of skills across two distant domains, for example music and mathematics) (Sala & Gobet, 2017).

Despite the rich relevant literature, it remains difficult to provide a complex model describing how music affects the different cognitive, linguistic, and motor functions for the following reasons:

1. Music is a multi-faceted phenomenon; it has numerous forms (e.g., listening to, creating or playing music), however, researchers studying these different aspects are still referring to these various activities by using the same terms (Schulze et al., 2012; Mansouri et al., 2017);
2. Music has different roles in different situations: it can be a means for an end, as in therapy; it can be the end itself in artistic or intellectual endeavor as it happens in composing, performance or pedagogy; it can also be the subject of a study as in music theory; or the object of an aesthetic experience, and so on (Abrams, 2011; Guetin et al., 2013, Francois et al., 2013; Krick et al., 2017);
3. The methods - how music is used in intervention - vary widely (music may be used in its entire complexity or there could be specific focus on different musical elements, such as meter, rhythm, melody, harmony, pitch, tonality, or volume);
4. The timeframe of music intervention may also differ across studies (the effects of music may vary over time) (Boso et al., 2007; Aalbers et al., 2017; Bugos & DeMarie, 2017);
5. The effects of different musical methods also differ depending on the target population, e.g., subjects without relevant health problems; patients with brain injury, or cognitive delay (Hutter et al., 2014; Lesiuk et al., 2018; Cooper, 2019);
6. Finally, inconsistent results in different studies may be related to a lack of specific music instruction use: results of recent studies strongly suggest that far-transfer effects of active music participation depend on the nature of the instruction used in music-making (Norgaard et al., 2019).

For these reasons we need to distinguish and specify the terms “*musical activities*” and “*music training*”. The former term is used as an umbrella term for any kind of musical activities where music can be both the goal and/or the tool in the process. Participants may exhibit different levels of musical proficiency (from none to high proficiency), and they may be a more passive or an active member during the process. The latter term refers to music studies (learning to play an instrument or to sing, typically in a music school or from a private teacher), where playing music is a goal and the process itself may involve many different types of musical activities in a complex way.

While the overall topic of this paper is the relationship between musical activities and cognitive control, we will focus on the developmental aspect of music. In the present chapter, we report results from a musical training study and based on the findings, we discuss the implications of musical activities in general.

Music – improving cognitive control

According to various training studies, cognitive control skills can be improved through targeted tasks and exercises (Diamond, 2012; Kolb et al., 2012; Diamond & Fiske, 2013, Janus et al., 2016). A large body of research indicates that musical activities can provide effective tools and structures for cognitive control improvement (Thaut et al., 2009; Thaut, 2010; Siepsiak & Krejtz, 2016; Guo et al., 2018). Nonetheless, studies focusing on the effects of musical activities on cognitive control functions are still rare.

The results of a longitudinal study indicate a positive influence of long-term music education on cognitive abilities such as inhibition and planning, and support a far transfer effect from music education in primary school children to academic achievement mediated by cognitive control sub-functions (Jaschke et al., 2018). Music’s benefits have been attributed to the practice of intensive memorization, visuo-motor skills, focused attention and the use of shared performance cues required for learning and performing music (Chaffin, 2007; Pallesen et al., 2010; De Dreu et al., 2012, Matthews & Kitsantas, 2013).

The following studies investigate the notion of a *modality-general* (regardless modality, both audio and visual) but *process-specific* (limited to specific processes of cognitive control) relationship between musical abilities and cognitive control skills – which have important connections to our later introduced research topic.

Zuk and colleagues compared musically trained and untrained children and adults on various cognitive control tasks (Zuk et al., 2014, Zuk et al., 2018). Both children and adults with musical training outperformed their untrained peers in different cognitive tasks (not modality specific), however, the group differences were not general (i.e. process-specific). Musically trained adults performed better than their untrained peers on measures of cognitive flexibility, verbal fluency and working memory measured by a standardized executive function battery. Children’s groups were also investigated using functional Magnetic Resonance Imaging (fMRI) to monitor the neural

correlates of cognitive functions. The two groups of children differed in measures of verbal fluency and processing speed, and musically trained children showed significantly greater activation in the pre-Supplementary Motor Area (pre-SMA) / Supplementary Motor Area (SMA) and the right Ventrolateral Prefrontal Cortex (VLPFC) during rule representation and task-switching. Results support a modality-general but process-specific approach of musical activities influence on cognitive control.

Similarly, Slevc and colleagues investigated whether musical experience and ability predicts individual differences on inhibition, updating and switching - in both auditory and visual modalities (Slevc et al., 2016). Results show that musical ability predicted better performance on both auditory and visual updating tasks (a variety of potential confounds were controlled, like age, handedness, bilingualism, and socio-economic status). Another finding of this research was that musical ability was not clearly related to inhibitory control (as assessed with auditory and spatial Stroop tasks) or to cognitive flexibility (assessed with auditory and visual task switching tasks). Therefore, this study further supports the idea that cognitive advantages associated with musical ability are not limited to auditory processes, but are limited to specific aspects of cognitive control (Slevc et al., 2016). On the other hand Moreno and colleagues suggest in a study that musical experience might lead to general inhibitory control advantages (Moreno et al., 2015). The explanation might partly come from the difference between the theoretic backgrounds of these investigations. Inhibitory control is not a single function, it can be divided into response inhibition and several types of interference control (Botvinick et al., 2001). Previous studies that assessed the relationship between musical training and inhibitory control failed to investigate these separate components with the appropriate tools within the same experiment. It is also important to mention, that interference control (the ability to overcome distraction from irrelevant information) undergoes considerable improvement during childhood till the age of 13-14 and is fully developed in adults (Cragg, 2016), while response inhibition develops during preschool ages 4-6 (Davidson et al., 2006). These age dependent developmental components also interact with the relationship between musical ability and cognitive control.

Roden and colleagues' longitudinal study has shown that children with an 18-months long extended music education program (with 45 minutes of weekly instrumental music training) outperformed their peers in control group in working-memory capacity tasks. The computerized test battery included seven subtests, which address the central executive, the phonological loop and the visuospatial sketchpad components of Baddeley's working memory model. Results suggest that children receiving music training benefit specifically in those aspects of cognitive functioning that are strongly related to auditory information processing (Roden et al., 2014). In another study Moreno and colleagues have found that even a short-term, but intensive musical training with a computerized program can enhance verbal intelligence and executive functions tested with a go/no-go task (Moreno et al., 2011).

Taken together, musical activities have a positive effect on various cognitive control mechanisms in both children and adults. Former research is not unified regarding the modality dependent and process-specific nature of this effect, and neither the detailed mechanisms of this connection. Related literature is difficult to synthesize because of the following reasons:

1. Past studies have typically discussed cognitive control only generally without systematically differentiating between various aspects of cognitive control mechanisms.
2. Because of the differing theoretical frames, previous studies have used a variety of experimental tasks, evaluation methods, explanations.
3. There are also a wide variety of criteria used to distinguish musicians from non-musicians.
4. Relevant studies differ also in the definition of music (time frame, type of musical activity, is music a goal or a tool in the process, see previous section for full list).
5. The targeted populations are ranging from primary school children to elderly adults. (Slevc et al., 2016)

In the following section we present the preliminary findings of our current study which can help us to further explore the connection between musical activities and cognitive control.

Preliminary findings of our current research

In a current study of ours we look at the relationship between formal regular musical training and cognitive control in young adults. In the present paper we focus on *working memory updating*, which exemplifies the previously highlighted cognitive flexibility mechanisms. We used the *N-back paradigm* with manipulations in task complexity and variants of modalities to examine whether musical experience affects working memory updating performance.

Research Questions

1. Do musician and non-musician young adults differ in working memory updating if the tasks include interfering lures and manipulations of memory load?
2. Does the working memory performance differ perceptual modality (auditory vs visual) and stimulus type (especially pitch and timbre) of the test?

Hypotheses

Concerning question 1: According to Botvinick's conflict monitoring theory, we assume that the musician group will perform significantly better than the non-musician group, especially in the most demanding, third set size condition (Botvinick et al., 2001).

Concerning question 2: Previous research suggests that musicians perform better in the auditory modality than non-musicians (Ding et al., 2018),

especially in the pitch variant in which they get much experience through musical activities. However, as music training doesn't emphasize timbre variations (Schulze et al., 2012) we expect that the between-group difference will be less expressed with respect to timbre. Musicians' knowledge of musical regularities might also contribute to a different, more efficient strategy use and better working memory performance in the auditory tasks (Ding et al., 2018).

Methods

Participants

39 neurotypical young adults were recruited for this study (see Table 1). 18 were trained musicians (studying music for at least 6 years) and 21 had no experience with music (except general music lessons in elementary school). Participants in both groups were matched for age, gender and socioeconomic status. All participants were university students in Budapest: musicians from Kőbányai Music Studio, non-musicians from ELTE Bárczi Gusztáv Faculty of Special Needs of Education. Exclusion criteria included bilingualism, regular dancing lessons, experience in martial arts, yoga and computer games (life experiences which improve cognitive control according to literature). Participants' hearing was also tested previously (entrance criteria: min. 20 dB or more on both ears on speech frequencies (0,5-1-2 kHz), min 30 dB on 3 kHz, and 40 dB on 4 kHz).

Table 1

Demographic data of participants

	Non-musicians	Musicians
N	21	18
Average age	21.3	21.2
SD of age	1.39	0.81
Minimum age	19	20
Maximum age	25	23
% of women	76%	61%

Stimuli and procedure

The N-back task is a commonly used as continuous performance assessment that measures working memory updating. The encoding, refreshing and retrieval processes during this task require attribution of each stimulus (content) to the appropriate temporal position (context), known as content-context bindings. The variations of the task differ in set size, stimulus type and modularity (for example in a visual letter task the subject reads the letters from a screen, in an auditory letter task the test could consist of the experimenter reading a list of letters to the test subject).

In our research we used both visual (letters and shapes) and auditory (pitches and timbres) versions of the task to investigate whether modality type influences working memory performance. Subjects' task was to judge, on each trial, whether the current stimulus matched the one that was presented n steps prior (Wadhera et al., 2018). For set size, the number of items to be held in working memory varied across three conditions: 1-back, 2-back and 3-back. Lures were only used in the visual task; in the auditory tasks the lure ratio was set to zero (Tsuchida & Fellows, 2009). This choice was made because the auditory stimuli seemed, on the basis of pilot tests, much more difficult to memorise than shapes and letters. In our pilot runs we found that lures in the auditory tasks resulted in chance-level performance for most participants.

In the proactive interference condition, 25% of the distractor items were lures presented prior to a target item at $n-1$ and $n-2$ positions. This condition was designed to measure the effect of previous target items presented as distractors on working memory updating performance across set sizes. In the retroactive interference condition, 25% of the distractor items were lures presented after a target item at $n+1$ and $n+2$ positions. This condition was designed to measure the effect of post target presentation of previous distractor items in incorrect temporal positions on working memory updating performance. Because of the nature of retroactive interference, it could only be manipulated in set sizes higher than the 1-back.

Testing took place in a quiet room at ELTE Bárczi Gusztáv Faculty of Special Needs of Education. The tasks were presented on the screen or via headphone, using E-prime software on a laptop, which collected accuracy and response time data. The laptop keyboard was used for response selection. The researcher provided detailed instructions and practice time (there was a 65% correct answer entrance limit to the test). There was an interval of 2400 ms between each stimulus item, which were presented for 600 ms. Participants were required to press the green button for a target and the red button for a distractor placed on the "M" or "X" keys. Location of the response buttons on the keyboard and presentation order of each condition were both counterbalanced across participants.

The letter and shape paradigms included eight conditions including three set size conditions: 1-back, 2-back and 3-back. Each set size included a neutral and a proactive condition. In addition, the 2 and 3-back set sizes also included a retroactive condition. The pitch and the timbre paradigm included only 2 conditions: 2-back and 3-back.

Table 2*N-back variations used in the current study*

Modality	Stimulus	Distractor	1-back	2-back	3-back
auditory	timbre	none		✓	✓
	pitch	none		✓	✓
visual	letter	none	✓	✓	✓
		proactive	✓	✓	✓
		retroactive		✓	✓
	shape	none	✓	✓	✓
		proactive	✓	✓	✓
		retroactive		✓	✓

Data Analysis

There were three dependent variables used to analyze data for this task. *Accuracy* was defined as percentage of correct answers. For *reaction time* (measured in ms) we calculated mean, median, and trimmed mean (20% trimming). To characterize *sensitivity* we calculated (i) d' primes (d') according to signal detection theory (SDT) and also (ii) hit/false alarm (HF) ratios. Since d' and HF ratios are non-linearly related, they may produce substantially different results in linear correlation tests. In particular, we were interested in correlations between RT on the one hand, and accuracy and sensitivity on the other, hence we used both accuracy, and the two sensitivity indicators in our analyses. Independent variables included previous musical experience (musicians/non-musicians), type of stimulus, set size, and presence of interference items.

The statistical methods used in the analysis were one-way comparison of independent samples, two-way mixed ANOVA and correlation tests. Since preliminary tests have shown that the distribution of our dependent variables was not normal, robust and nonparametric tests were used to analyze the outcomes.

Results

One of our main questions was whether musician and non-musician young adults differ in working memory updating. After type-I error correction no significant differences in reaction time or accuracy were found between the two groups: see *Tables 3* and *4*.

Table 3
Average reaction time

modality	type of test		set size	average reaction time		Cohen's d	Welch test		Yuen test	
	stimulus	distractor		non-musicians	musicians		t	p	Y	p
auditory	timbre	none	2	1501,10	1358,00	0,256	0,798	0,4305	0,288	0,7760
		none	3	1361,80	1263,00	0,162	0,507	0,6156	0,002	0,9985
	pitch	none	2	1184,80	1107,10	0,214	0,641	0,5259	0,845	0,4081
		none	3	1257,50	1211,80	0,096	0,293	0,7712	-0,274	0,7864
visual	letter	none	1	623,03	568,19	0,237	0,737	0,4680	0,237	0,8152
		proactive	1	590,28	556,00	0,193	0,599	0,5541	-0,341	0,7366
		none	2	605,06	570,59	0,215	0,654	0,5178	0,512	0,6141
		proactive	2	631,17	589,23	0,222	0,663	0,5127	0,225	0,8244
		retroactive	2	610,72	568,71	0,218	0,669	0,5084	0,280	0,7823
		none	3	623,78	580,73	0,223	0,681	0,5008	0,141	0,8891
	shape	proactive	3	616,14	588,40	0,158	0,478	0,6361	0,223	0,8261
		retroactive	3	613,37	617,82	-0,024	-0,072	0,9429	-0,192	0,8496
		none	1	527,28	570,27	-0,323	-0,949	0,3501	-0,622	0,5409
		proactive	1	522,05	561,72	-0,345	-1,027	0,3122	-0,600	0,5548
		none	2	595,83	658,54	-0,300	-0,867	0,3930	-0,791	0,4387
		proactive	2	572,15	664,75	-0,415	-1,224	0,2300	-1,322	0,2024
visual	shape	retroactive	2	587,20	632,51	-0,230	-0,683	0,4996	-1,044	0,3089
		none	3	572,55	667,88	-0,438	-1,312	0,1983	-1,337	0,1950
	shape	proactive	3	613,95	682,66	-0,268	-0,819	0,4189	-1,157	0,2604
		retroactive	3	586,56	672,91	-0,375	-1,126	0,2682	-1,334	0,1969

Table 4
Accuracy

modality		type of test			average reaction time		Cohen's d	Welch test		Yuen test		
		stimulus	distractor	set size	non-musicians	musicians		t	p	Y	p	
auditory	timbre	none	none	2	0,765	0,822	-0,386	-1,202	0,2376	-1,373	0,1897	
		none	none	3	0,682	0,709	-0,245	-0,740	0,4643	-0,829	0,4195	
	pitch	none	none	2	0,848	0,940	-0,832	-2,634	* 0,0131	-2,384	* 0,0329	
		none	none	3	0,720	0,790	-0,618	-1,889	0,0672	-1,973	0,0629	
	visual	letter	none	none	1	0,949	0,956	-0,204	-0,608	0,5471	-0,793	0,4391
			proactive	proactive	1	0,927	0,916	0,142	0,413	0,6830	-0,487	0,6310
none			none	2	0,912	0,946	-0,506	-1,557	0,1300	-1,773	0,0922	
proactive			proactive	2	0,847	0,904	-0,613	-1,823	0,0782	-1,433	0,1675	
retroactive			retroactive	2	0,914	0,925	-0,155	-0,468	0,6424	-0,540	0,5949	
none			none	3	0,857	0,886	-0,342	-1,027	0,3116	-1,125	0,2746	
visual	shape	proactive	proactive	3	0,806	0,849	-0,471	-1,390	0,1739	-1,374	0,1848	
		retroactive	retroactive	3	0,804	0,866	-0,723	-2,148	* 0,0392	-1,704	0,1059	
		none	none	1	0,871	0,935	-0,477	-1,448	0,1640	-0,971	0,3469	
		proactive	proactive	1	0,850	0,926	-0,614	-1,934	0,0674	-1,436	0,1685	
		none	none	2	0,797	0,860	-0,483	-1,484	0,1482	-1,030	0,3159	
		proactive	proactive	2	0,768	0,838	-0,562	-1,689	0,1029	-1,383	0,1813	
visual	shape	retroactive	retroactive	2	0,819	0,876	-0,452	-1,351	0,1870	-1,137	0,2685	
		none	none	3	0,764	0,831	-0,600	-1,845	0,0749	-1,621	0,1194	
		proactive	proactive	3	0,723	0,771	-0,387	-1,168	0,2511	-0,684	0,5044	
visual	shape	retroactive	retroactive	3	0,721	0,768	-0,436	-1,311	0,1987	-1,265	0,2191	

We also looked at whether the working memory performance of the two groups differed according to the modularity type (audio or visual). We hypothesized that group differences would be obtained with pitch stimuli. This hypothesis is supported: we found that in terms of accuracy and sensitivity to pitches musicians outperformed non-musicians (see Table 4. for accuracy, and table 5. for sensitivity)

Table 5

Sensitivity

test type	sensitivity (d')		Cohen's d	Welch test		Yuen test	
	non-musicians	musicians		t	p	Y	p
2-back pitch	2,281	3,193	-0,911	-2,815	** 0,0080	-2,713	* 0,0145
3-back pitch	1,144	1,642	-0,607	-1,834	0,0755	-2,217	* 0,0378

Since there were no significant differences in reaction time between the two groups in these tasks (see *Table 3.*) - this means that musicians tend not to be faster, but more accurate with pitch stimuli than their non-musician peers.

Finally, the effect of group and stimulus type on three indicators of cognitive control functions (RT, per cent of correct responses [accuracy], and d -prime) was examined in two-way mixed ANOVAS (Group (2) X Stimulus type(4)-within-subjects), for the to-back and three-back tasks separately. The results are summarized in *tables 6.a.* and *6.b.* In terms of speed the groups did not differ. There was, however, a marginally significant between-group difference ($p < 0.1$) both in the accuracy and d -prime scores in the 2-back condition, and one for accuracy in the 3-back condition. In all these cases musicians performed better (see *tables 6a* and *6b* for the corresponding *group by stimulus type* means). Next, the effect of stimulus type was significant for each of the three dependent variables, for both set sizes. There was no interaction anywhere.

Table 6a
ANOVA for 2-back tests

Indicator	group	stimulus type				Welch's test for group effect		Geisser-Greenhouse's test of type effect		Geisser-Greenhouse's test of interaction effect	
		timbre	pitch	letter	shape	F	p	F	p	F	p
Average reaction time	non-musicians	1503,9	1165,9	605,1	595,8	0,246	0,6228	64,786	0,0000	0,814	0,3732
	musicians	1358,0	1107,1	570,6	671,6						
ACC	non-musicians	0,768	0,845	0,912	0,797	4,068	0,0541	18,397	0,0001	0,787	0,3813
	musicians	0,822	0,940	0,946	0,854						
d'	non-musicians	1,616	2,258	2,649	1,538	4,073	0,0524	24,522	0,0000	1,293	0,2635
	musicians	1,901	3,193	3,133	1,967						

Table 6b
ANOVA for 3-back tests

Indicator	group	stimulus type				Welch's test for group effect		Geisser-Greenhouse's test of type effect		Geisser-Greenhouse's test of interaction effect	
		timbre	pitch	letter	shape	F	p	F	p	F	p
Average reaction time	non-musicians	1377,6	1276,7	623,8	572,6	0,411	0,5265	45,196	0,0000	0,760	0,3896
	musicians	1263,0	1130,1	576,5	649,7						
ACC	non-musicians	0,680	0,726	0,857	0,764	3,565	0,0679	41,123	0,0000	1,110	0,2998
	musicians	0,709	0,805	0,894	0,836						
d'	non-musicians	0,869	1,194	2,012	1,163	1,828	0,1855	30,872	0,0000	0,550	0,4633
	musicians	0,999	1,642	2,345	1,554						

Due to the absence of interaction, and the modest or missing between-group differences, we decided to unite the two groups, and examine the effect of stimulus type in more detail. Figure 1 shows the corresponding graphs, and the results of post hoc tests (Tukey) are summarized in Table 7.

Figure 1

The effect of stimulus type on the three dependent variables: reaction time, accuracy – per cent of correct responses, and d-prime (Black bars show the means (based on the entire sample), gray caps represent CI95 half-width.)

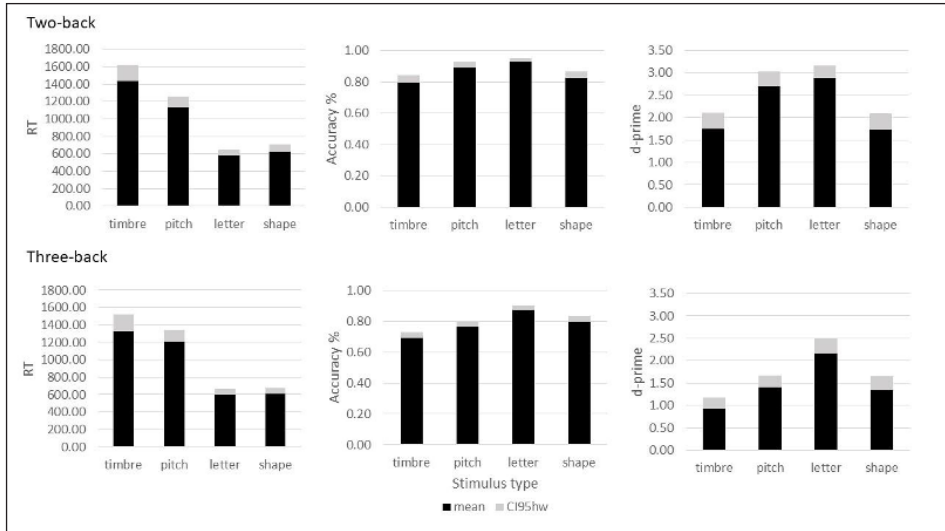


Table 7

*Summary of post hoc Tukey tests for the effect of stimulus type in the six ANOVAs (Abbreviations and symbols: tmb – timbre, ptc – pitch, lett – letter, shp – shape; *: $p < 0.05$; **: $p < 0.01$.)*

Indicator		timbre-pitch	timbre-letter	timbre-shape	picture-letter	picture-shape	letter-shape
2-back	Average reaction time	5,88**	16,76**	15,91**	10,88**	10,03**	0,85
	ACC	6,76**	9,46**	2,15	2,7	4,61*	7,31**
	d'	7,69**	9,14**	0,08	1,44	7,78**	9,22**
3-back	Average reaction time	2,04	12,78**	12,68**	10,73**	10,63**	0,1
	ACC	5,89**	15,46**	8,85**	9,56**	2,96	6,60**
	d'	5,11**	13,31**	4,48*	8,21**	0,63	8,84**

The pattern is quite similar for the two set sizes. With respect to RT, letters and shapes did not differ. Subjects were faster with pitch than with timbre

in the two-back condition; however, this difference did not reach significance in the three-back condition. Responses to both pitch and timbre were slower than those to any of the visual stimulus types. Regarding performance, accuracy and d-prime show essentially the same pattern, although not exactly the same differences were significant in the two set size conditions. Timbre was more difficult than pitch, for both set sizes. Letters and shapes were not equally difficult (despite producing identical reaction times). Letters proved substantially easier than shapes. Letters were easier than timbres, for both set sizes. Shapes were easier than timbres when the working memory load was higher (3-back); not so, however, when it was smaller (2-back); the same was true of the relationship between pitches and letters (pitches were easier in 3-back, but not in 2-back). Interestingly the opposite trend was observed for pitches and shapes: pitches were easier than shapes when the working memory-load was smaller (2-back), but this difference disappeared with higher memory load (3-back).

Discussion

The present research aimed to explore the relationship between musical training and cognitive control abilities in young adults. Working memory updating performance was used to measure and illustrate how mechanisms of cognitive flexibility manifest in students with different musical experiences. There are two main findings to be discussed.

First, working memory updating performance doesn't clearly distinguish musician and non-musician young adults - although in terms of accuracy musicians performed better than non-musician.

Second, musicians' accuracy was significantly better in the pitch tasks of the auditory modality, but not in the timbre N-backs - while there was no significant difference in reaction time.

According to Botvinick's conflict monitoring theory (Botvinick et al., 2001) and former research with professional musicians (Herholz & Zatorre, 2012; Fennell et al., 2020; Chen et al., 2020) and previous studies on the long-term effect of musical training on working memory updating (Nutley et al., 2014) we assumed, that the group of musicians would perform significantly better than the non-musician group. In terms of reaction time we did not find a significant difference, and there was only a slight trend showing that musicians performed more accurately than non-musicians. Regarding accuracy musician performed significantly better in pitch tasks, for further details and possible explanations pls. see next paragraph. Investigating the lack of group difference in reaction time and accuracy in the most tasks, one explanation can be that participants of previous research were professional classical musicians, while our subjects were jazz and pop musicians. Given that training in classical music (including playing instruments) supports the development of other skills including cognitive control, it is reasonable to assume that jazz and pop music can do so as well. Earlier studies relied on cognitive control frameworks other than Cohen's CC paradigm, and Botwinick's theory, so failed to distinguish

the different mechanisms of cognitive control from each other (like response inhibition and types of interference) in the same experiment and used also different working memory concepts (for example, Baddeley's or Cowan's). These studies used different assessment tasks, so their results are not directly comparable to ours (Schulze et al., 2012, Berz, 1995).

Our finding that musicians' accuracy was significantly better in the pitch tasks than that of non-musicians, is paralleled by similar results in the literature (Schulze et al., 2012; Fennell et al., 2020). In a recent experiment Fennel and colleagues found, that young musicians performed more accurately on the working memory tasks than their non-musician peers, particularly for the verbal and musical working memory stimuli – while have shown no significant difference on working memory tasks with visuospatial stimuli. Musicians' knowledge of musical regularities might also contribute to a different, more efficient strategy use and due to this a better working memory performance in the auditory tasks (Ding et al., 2018). After summarizing the questionnaires about the strategies of the subjects we might find further connections between musicians' performance, strategy and modality type in the future.

While our findings provided support for the relationship between regular musical activities and cognitive abilities, this relationship warrants further investigation. Our next analysis will be focused on the question whether the musician group rejects more proactive distractors than the non-musician peers. For this reason, we plan to compare the reaction times for all item types (target, new distractor, proactive distractor and retroactive distractor) and also examine the average and median of reaction time. A further question is whether any variables related to musicians' past experiences, such as age of onset of music training, hours of practicing per week, or type of instrument played predict working memory updating performance. We hypothesize that the age at which music training starts influences later working memory performance. This is because there is a sensitive period for music learning, hence music training with early onset has a long-term effect on cognitive control performance (Chen et al., 2020). Relying on recent studies, we also assume, that subjects in the musician group have different cognitive control performance profile according to the instrument they play (Porflitt & Rosas, 2020) and the groups instrument distribution can also influence the groups working memory performance.

Conclusion

In the 21st century life success depends increasingly on skills and competences which are related to the mastery of cognitive control processes such as goal setting, planning, organizing, prioritizing, memorizing, initiating, shifting and self-monitoring (Fadel & Trilling, 2009; Gropen et al., 2011). Findings in the literature suggest that music may support cognitive and emotional development in many ways (Trainor et al., 2009; Herholz & Zatorre, 2012; Miendlarzewska & Trost, 2014 ; Schroeder et al., 2016; Guo et al., 2018). Musical activities' transfer effects on cognitive control mechanisms came recently often in focus, although literature is not united in many details. (Okada & Slevc, 2018; Sala & Gobet, 2020).

Our first goal in the current paper was to provide a brief review of the literature about both music as an influential factor in cognitive development, and cognitive control. Further, with the help of the first results of our ongoing research, our aim was to introduce the underlying cognitive control mechanisms that might be affected by musical activities and to identify those components that can help us to develop more focused and effective methods for music intervention in education, and in developmental or clinical populations. Our first results support the working hypothesis that musical training may promote the development and maintenance of certain cognitive control skills, although the introduced investigations form only a section on the entrance level of our ongoing wider research.

Musical activities provide a safe and joyful context for practicing and exercising cognitive control and can contribute as an impactful and cost-effective tool to improve 21st century skills. Further research in Cohens cognitive control theoretical frames, investigating musical activities effect on the separate cognitive control components can lead us to more detailed, comparable information and appropriate application of musical tools in education, development, and healthcare.

References

- Aalbers, S., Spreen, M., Bosveld, L., van Haandel & Bogaerts, S. (2017). Evaluation of client progress in music therapy: an illustration of an N-of-1 design in individual short-term improvisational music therapy with clients with depression. *Nordic Journal of Music Therapy*, 26(3), 256–271. <https://doi.org/10.1080/08098131.2016.1205649>
- Abrams, B. (2011). Understanding music as a temporal-aesthetic way of being: Implications for a general theory of music therapy. *Arts in Psychotherapy*, 38(2), 114–119. <https://doi.org/10.1016/j.aip.2011.02.001>
- Berz, W. (1995). Working-Memory In Music - A Theoretical-Model. *Music Perception*, 12(3), 353–364. <https://doi.org/10.2307/40286188>
- Boso, M., Emanuele, E., Minazzi, V., Abbamonte, M. & Politi, P. (2007). Effect of long-term interactive music therapy on Behavior profile and musical skills in young adults with severe autism. *Journal of Alternative and Complementary Medicine*, 13(7), 709–712. <https://doi.org/10.1089/acm.2006.6334>
- Botvinick, M., Braver, T., Barch, D., Carter, C. & Cohen, J. (2001). Conflict monitoring and cognitive control. *Psychological Review*, 108(3), 624–652. <https://doi.org/10.1037/0033-295x.108.3.624>
- Botvinick, M. & Cohen, J. (2014). The Computational and Neural Basis of Cognitive Control: Charted Territory and New Frontiers. *Cognitive Science*, 38(6), 1249–1285. <https://doi.org/10.1111/cogs.12126>
- Brock, L., Rimm-Kaufman, S., Nathanson, L. & Grimm, K. (2009). The contributions of ‘hot’ and ‘cool’ executive function to children’s academic achievement, learning-related behaviors, and engagement in kindergarten. *Early Childhood Research Quarterly*, 24(3), 337–349. <https://doi.org/10.1016/J.ECRESQ.2009.06.001>

- Brookes, D. T., Ross, B. H. & Mestre, J. P. (2011). Specificity, transfer, and the development of expertise. *Physical Review Special Topics-Physics Education Research*, 7. <https://doi.org/10.1103/PhysRevSTPER.7.010105>
- Bugos, J. & DeMarie, D. (2017). The effects of a short-term music program on preschool children's executive functions. *Psychology of Music*, 45, 855–867. <https://doi.org/10.1177/0305735617692666>
- Chaffin, R. (2007). Learning Clair de Lune: Retrieval practice and expert memorization. *Music Perception*, 24(4), 377–393. <https://doi.org/10.1525/mp.2007.24.4.377>
- Chen, J. J., Scheller, M., Wu, C. Y., Hu, B. Y., Peng, R., Liu, C. H., Liu, S. Y., Zhu, L. W. & Chen, J. (2021). The relationship between early musical training and executive functions: Validation of effects of the sensitive period. *Psychology of Music*, <https://doi.org/10.1177/0305735620978690>
- Chen, J. J., Zhou, Y. & Chen, J. (2020). The relationship between musical training and inhibitory control: An ERPs study. *Acta Psychologica Sinica*, 52(12), 1365–1376. <https://doi.org/10.3724/SP.J.1041.2020.01365>
- Cohen, J. D. (2017). Cognitive Control - Core Constructs and Current Consideration. In *The Wiley Handbook of Cognitive Control* (pp. 3–28), Wiley-Blackwell. <https://doi.org/10.1002/9781118920497.ch1>
- Cooper, P. K. (2019). It's all in your head: A meta-analysis on the effects of music training on cognitive measures in schoolchildren. *International Journal of Music Education*, 38(3), <https://doi.org/10.1177/0255761419881495>
- Cragg, L. (2016). The Development of Stimulus and Response Interference Control in Midchildhood. *Developmental Psychology*, 52(2), 242–252. <http://dx.doi.org/https://doi.org/10.1037/dev0000074>
- Davidson, M. C., Amso, D., Anderson, L. C. & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia*, 44(11), 2037–2078. <https://doi.org/10.1016/j.neuropsychologia.2006.02.006>
- De Dreu, C., Nijstad, B., Baas, M., Wolsink, I. & Roskes, M. (2012). Working Memory Benefits Creative Insight, Musical Improvisation, and Original Ideation Through Maintained Task-Focused Attention. *Personality and Social Psychology Bulletin*, 38(5), 656–669. <https://doi.org/10.1177/0146167211435795>
- de Vries, M., Prins, P., Schmand, B. & Geurts, H. (2015). Working memory and cognitive flexibility-training for children with an autism spectrum disorder: a randomized controlled trial. *Journal of Child Psychology and Psychiatry*, 56(5), 566–576. <https://doi.org/10.1111/jcpp.12324>
- de Zeeuw, P., Weusten, J., van Dijk, S., van Belle, J. & Durston, S. (2012). Deficits in Cognitive Control, Timing and Reward Sensitivity Appear to be Dissociable in ADHD. *Plos One*, 12(7), <https://doi.org/10.1371/journal.pone.0051416>
- Diamond, A. (2012). Activities and Programs That Improve Children's Executive Functions. *Current Directions in Psychological Science*, 21(5), 335–341. <https://doi.org/10.1177/0963721412453722>

- Diamond, A. & Fiske, S. (2013). Executive Functions. *Annual Review of Psychology*, 64, 135–168. <https://doi.org/10.1146/annurev-psych-113011-143750>
- Ding, Y., Gray, K., Forrence, A., Wang, X. Q. & Huang, J. (2018). Behavioral study on tonal working memory in musicians and non-musicians. *Plos One*, 13(8), 18. <https://doi.org/10.1371/journal.pone.0201765>
- Dudukovic, N. M. & Kuhl, B. A. (2017). Cognitive control in memory encoding and retrieval. In *The Wiley Handbook of Cognitive Control* (pp. 357–375). Wiley & Blackwell. <https://doi.org/10.1002/9781118920497.ch20>
- Egner, T. & Hirsch, J. (2005). Cognitive control mechanisms resolve conflict through cortical amplification of task-relevant information. *Nature Neuroscience*, 8(12), 1784–1790. <https://doi.org/10.1038/nn1594>
- Fadel, C. & Trilling, B. (2009). *21st century skills: Learning for life in our times*. Jossey-Bass.
- Fennell, A. M., Bugos, J. A., Payne, B. R. & Schotter, E. R. (2020). Music is similar to language in terms of working memory interference. *Psychonomic Bulletin & Review*, 28(2), 512-525. <https://doi.org/10.3758/s13423-020-01833-5>
- Francois, C., Chobert, J., Besson, M. & Schon, D. (2013). Music Training for the Development of Speech Segmentation. *Cerebral Cortex*, 23(9), 2038–2043. <https://doi.org/10.1093/cercor/bhs180>
- Gropen, J., Clark-Chiarelli, N., Hoisington, C. & Ehrlich, S. (2011). The Importance of Executive Function in Early Science Education. *Child Development Perspectives*, 5(4), 298–304. <https://doi.org/10.1111/j.1750-8606.2011.00201.x>
- Guetin, S., Charras, K., Berard, A., Arbus, C., Berthelon, P., Blanc, F., Blayac, J., Bonte, F., Bouceffa, J., Clement, S., Ducourneau, G., Gzil, F., Laeng, N., Lecourt, E., Ledoux, S., Platel, H., Thomas-Anterion, C., Touchon, J., Vrait, F. & Leger, J. (2013). An overview of the use of music therapy in the context of Alzheimer’s disease: A report of a French expert group. *Dementia-International Journal of Social Research and Practice*, 12(5), 619–634. <https://doi.org/10.1177/1471301212438290>
- Guo, X., Ohsawa, C., Suzuki, A. & Sekiyama, K. (2018). Improved Digit Span in Children after a 6-Week Intervention of Playing a Musical Instrument: An Exploratory Randomized Controlled Trial. *Frontiers in Psychology*, 8. <https://doi.org/10.3389/fpsyg.2017.02303>
- Herholz, S. & Zatorre, R. (2012). Musical Training as a Framework for Brain Plasticity: Behavior, Function, and Structure. *Neuron*, 76(3), 486–502. <https://doi.org/10.1016/j.neuron.2012.10.011>
- Hogeveen, J., Krug, M., Elliott, M., Carter, C. & Solomon, M. (2017). Proactive Cognitive Control as a Double-Edged Sword in Autism Spectrum Disorder. *Neuropsychopharmacology*, 127(4), 429-435. <https://doi.org/10.1037/abn0000345>
- Hutter, E., Grapp, M., Argstatter, H. & Bolay, H. (2014). Music Therapy for Chronic Tinnitus: Variability of Tinnitus Pitch in the Course of Therapy. *Journal of the American Academy of Audiology*, 25(4), 335–342. <https://doi.org/10.3766/jaaa.25.4.5>

- Jacobson, L., Williford, A. & Pianta, R. (2011). The role of executive function in children's competent adjustment to middle school. *Child Neuropsychology*, 17(3), 255–280. <https://doi.org/10.1080/09297049.2010.535654>
- Janus, M., Lee, Y., Moreno, S. & Bialystok, E. (2016). Effects of short-term music and second-language training on executive control. *Journal of Experimental Child Psychology*, 144, 84–97. <https://doi.org/10.1016/j.jecp.2015.11.009>
- Jarrett, M., Gilpin, A., Pierucci, J. & Rondon, A. (2016). Cognitive and reactive control processes: Associations with ADHD symptoms in preschoolers. *International Journal of Behavioral Development*, 40, 53–57. <https://doi.org/10.1177/0165025415575625>
- Jaschke, A. C., H. Honing & E. J. A. Scherder (2018). Longitudinal Analysis of Music Education on Executive Functions in Primary School Children. *Frontiers in Neuroscience*, 12(103), 1-11. <https://doi.org/10.3389/fnins.2018.00103>
- Kolb, B., Mychasiuk, R., Muhammad, A., Li, Y., Frost, D. & Gibb, R. (2012). Experience and the developing prefrontal cortex. *Proceedings of the National Academy of Sciences of the United States of America*, 109(2), 17186–17193. <https://doi.org/10.1073/pnas.1121251109>
- Krick, C., Argstatter, H., Grapp, M., Plinkert, P. & Reith, W. (2017). Heidelberg Neuro-Music Therapy Restores Attention-Related Activity in the Angular Gyrus in Chronic Tinnitus Patients. *Frontiers in Neuroscience*, 11. <https://doi.org/10.3389/fnins.2017.00418>
- Lesiuk, T., Bugos, J. A. & Murakami, B. (2018). A Rationale for Music Training to Enhance Executive Functions in Parkinson's Disease: An Overview of the Problem. *Healthcare*, 6(2), 35. <https://doi.org/10.3390/healthcare6020035>
- Mansouri, F. A., Acevedo, N., Illiparampil, R., Fehring, D. J., Fitzgerald, P. B. & Jaberzadeh, S. (2017). Interactive effects of music and prefrontal cortex stimulation in modulating response inhibition. *Scientific Reports*, 7(1), 18096. <https://doi.org/10.1038/s41598-017-18119-x>
- Marton, K. (2016). Executive control in bilingual children Factors that influence the outcomes. *Linguistic Approaches To Bilingualism*, 6(5), 575–589. <https://doi.org/10.1075/lab.15038.mar>
- Marton, K., Campanelli, L., Eichorn, N., Scheuer, J. & Yoon, J. (2014). Information Processing and Proactive Interference in Children With and Without Specific Language Impairment. *Journal of Speech Language and Hearing Research*, 57(1), 106–119. [https://doi.org/10.1044/1092-4388\(2013/12-0306\)](https://doi.org/10.1044/1092-4388(2013/12-0306))
- Marton, K., Eichorn, N., Campanelli, L. & Zakarias, L. (2016). Working Memory and Interference Control in Children with Specific Language Impairment. *Language and Linguistics Compass*, 10(5), 211;224. <https://doi.org/10.1111/lnc3.12189>
- Marton, K., Goral, M., Campanelli, L., Yoon, J. & Obler, L. (2017). Executive control mechanisms in bilingualism: Beyond speed of processing. *Bilingualism-Language and Cognition*, 20(3), 613–631. <https://doi.org/10.1017/S1366728915000930>
- Matthews, W. & Kitsantas, A. (2013). The role of the conductor's goal orientation and use of shared performance cues on collegiate instrumentalists' motivational beliefs

- and performance in large musical ensembles. *Psychology of Music*, 41(5), 630–646. <https://doi.org/10.1177/0305735612441738>
- Miendlarzewska, E. & Trost, W. (2014). How musical training affects cognitive development: rhythm reward and other modulating variables. *Frontiers in Neuroscience*, 7, <https://doi.org/10.3389/fnins.2013.00279>
- Moreno, S., Bialystok, E., Barac, R., Schellenberg, E., Cepeda, N. & Chau, T. (2011). Short-Term Music Training Enhances Verbal Intelligence and Executive Function. *Psychological Science*, 22(11), 1425–1433. <https://doi.org/10.1177/0956797611416999>
- Moreno, S., Farzan, F., Bigand, E., Tillmann, B., Zatorre, R., Lopez, L. & Majno, M. (2015). Music training and inhibitory control: a multidimensional model. *Neurosciences and Music V: Cognitive Stimulation and Rehabilitation*, 1337, 147–152. <https://doi.org/10.1177/0305735620978690>
- Norgaard, M., Stambaugh, L. A. & McCranie, H. (2019). The Effect of Jazz Improvisation Instruction on Measures of Executive Function in Middle School Band Students. *Journal of Research in Music Education*, 67, 339–354. <https://doi.org/10.1177/0022429419863038>
- Nutley, S., Darki, F. & Klingberg, T. (2014). Music practice is associated with development of working memory during childhood and adolescence. *Frontiers in Human Neuroscience*, 7(7), 926. <https://doi.org/10.3389/fnhum.2013.00926>
- Okada, B. M. & Slevc, L. R. (2018). Individual differences in musical training and executive functions: A latent variable approach. *Memory & Cognition*, 46(7), 1076–1092. <https://doi.org/10.3758/s13421-018-0822-8>
- Pallesen, K., Brattico, E., Bailey, C., Korvenoja, A., Koivisto, J., Gjedde, A. & Carlson, S. (2010). Cognitive Control in Auditory Working Memory Is Enhanced in Musicians. *Plos One*, 5(6), E11120. <https://doi.org/10.1371/journal.pone.0011120>
- Porflitt, F. & Rosas, R. (2020). Core music elements: rhythmic, melodic and harmonic musicians show differences in cognitive performance (Elementos basicos de la musica: músicos ritmicos, melodicos y armonicos muestran diferencias de desempeño cognitivo). *Studies in Psychology*, 41(3), 532–562. <https://doi.org/10.1080/02109395.2020.1795493>
- Rhoades, B., Greenberg, M. & Domitrovich, C. (2009). The contribution of inhibitory control to preschoolers' social-emotional competence. *Journal of Applied Developmental Psychology*, 30(3), 310–320. <https://doi.org/10.1016/j.appdev.2008.12.012>
- Roden, I., Grube, D., Bongard, S. & Kreutz, G. (2014). Does music training enhance working memory performance? Findings from a quasi-experimental longitudinal study. *Psychology of Music*, 42(2), 284–298. <https://doi.org/10.1177/0305735612471239>
- Sala, G. & Gobet, F. (2017). When the music's over. Does music skill transfer to children's and young adolescents' cognitive and academic skills? A meta-analysis. *Educational Research Review*, 20, 55–67. <https://doi.org/10.1016/j.edurev.2016.11.005>

- Sala, G. & Gobet, F. (2020). Cognitive and academic benefits of music training with children: A multilevel meta-analysis. *Memory & Cognition*, 48(8), 1429–1441. <https://doi.org/10.3758/s13421-020-01060-2>
- Schneider, W. & Shiffrin, R. (1977). Controlled and automatic human information-processing.1. Celection, search, and attention. *Psychological Review*, 84(1), 1–66. <https://doi.org/10.1037/0033-295X.84.1.1>
- Schroeder, S. R., Marian, V., Shook, A. & Bartolotti, J. (2016). Bilingualism and Musicianship Enhance Cognitive Control. *Neural Plasticity*. <https://doi.org/10.1155/2016/4058620>
- Schulze, K., Koelsch, S. & Annals, N. Y. A. S. (2012). Working memory for speech and music. *Neurosciences and Music Iv: Learning and Memory*, 1252, 229–236. <https://doi.org/10.1111/j.1749-6632.2012.06447.x>
- Shiffrin, R. & Schneider, W. (1977). Controlled and automatic human information-processing.2. Perceptual learning,automatic attending, and general theory. *Psychological Review*, 84(2), 127–190. <https://doi.org/10.1037/0033-295X.84.2.127>
- Siepsiak, M. & Krejtz, I. (2016). Does music therapy improve executive functions after stroke, and how to check it? *Nordic Journal of Music Therapy*, 25(1), 68–68. <https://doi.org/10.1080/08098131.2016.11783620>
- Slevc, L. R., Davey, N. S., Buschkuehl, M. & Jaeggi, S. M. (2016). Tuning the mind: Exploring the connections between musical ability and executive functions. *Cognition*, 152, 199–211. <https://doi.org/10.1016/j.cognition.2016.03.017>
- Solomon, M., McCauley, J., Iosif, A., Carter, C. & Ragland, J. (2016). Cognitive control and episodic memory in adolescents with autism spectrum disorders. *Neuropsychologia*, 89, 31–41. <https://doi.org/10.1016/j.neuropsychologia.2016.05.013>
- Thaut, M. H. (2010). Neurologic Music Therapy In Cognitive Rehabilitation. *Music Perception*, 27(4), 281–285. <https://doi.org/10.1525/mp.20https://doi.org/10.27.4.281>
- Thaut, M. H., Gardiner, J. C., Holmberg, D., Horwitz, J., Kent, L., Andrews, G., Donelan, B. & McIntosh, G. R. (2009). Neurologic Music Therapy Improves Executive Function and Emotional Adjustment in Traumatic Brain Injury Rehabilitation. *Annals of the New York Academy of Sciences*, 1169(1), 406–416. <https://doi.org/10.1111/j.1749-6632.2009.04585.x>
- Trainor, L., Shahin, A., Roberts, L., DallaBella, S., Kraus, N., Overy, K., Pantev, C., Snyder, J., Tervaniemi, M., Tillmann, B. & Schlaug, G. (2009). Understanding the Benefits of Musical Training Effects on Oscillatory Brain Activity. *Neurosciences and Music Iii: Disorders and Plasticity*, 1169(1), 133–142. <https://doi.org/10.1111/j.1749-6632.2009.04589.x>
- Tsuchida, A. & Fellows, L. K. (2009). Lesion Evidence That Two Distinct Regions within Prefrontal Cortex are Critical for n-Back Performance in Humans. *Journal of Cognitive Neuroscience*, 21(12), 2263–2275. <https://doi.org/10.1162/jocn.2008.21172>
- Wadhwa, D., Campanelli, L. & Marton, K. (2018). The influence of bilingual language experience on working memory updating performance in young adults. In

- Rogers, T. T., Rau, M., Zhu, X. & Kalish, C. W. (Eds.), *Proceedings of the 40th Annual Conference of the Cognitive Science Society* (pp. 2639–2644). , Cognitive Science Society.
- Zatorre, R. & Salimpoor, V. (2013). From perception to pleasure: Music and its neural substrates. *Proceedings of the National Academy of Sciences of the United States of America*, *110*, 10430–10437. <https://doi.org/10.1073/pnas.1301228110>
- Zuk, J., Benjamin, C., A. Kenyon, A., & Gaab, N. (2014). Behavioral and Neural Correlates of Executive Functioning in Musicians and Non-Musicians. *Plos One*, *9*(6), 13. <https://doi.org/10.1371/journal.pone.0099868>
- Zuk, J., C. Benjamin, C., A. Kenyon, A., & N. Gaab, N. (2018). Behavioral and Neural Correlates of Executive Functioning in Musicians and Non-Musicians (vol 9, e99868, 2014). *Plos One*, *13*. <https://doi.org/10.1371/journal.pone.0191394>