NATIONAL AND KAPODISTRIAN UNIVERSITY OF ATHENS
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DEPARTMENT OF PSYCHOLOGY
DEPARTMENT OF PHILOLOGY

Alexandra – Christina Orfanou

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The contribution of musical rhythm to the processing of syntax and geometrical patterns of temporal and spatial hierarchy

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Advisory committee:
Spyridoula Varlokosta, Professor of Linguistics and Psycholinguistics,
National and Kapodistrian University of Athens
Argiro Vatakis, Assistant Professor of Psychology Department,
Panteion University of Social and Political Sciences, Athens, Greece
Irini Skaliora, Professor of Neuroscience,
National and Kapodistrian University of Athens and
Biomedical Research Foundation of the Academy of Athens

Athens, Greece
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The thesis is approved

Spyridoula Varlokosta...

Argiro Vatakis...

Irini Skaliora..

Abstract

Following findings from English- and Hungarian-speaking children, that musical rhythmic priming enhances subsequent syntactic processing of linguistic but not of other visuo-spatial or mathematical structures, we tested these effects in typically developing 11-year-old Greek-speaking children. Participants heard 32s musical sequences of strong metrical structure, weak metrical structure or silence. Then, they were visually presented with sentences, half of which had gender violations in the adjective-noun agreement, and were asked to perform grammaticality judgements. The same experimental framework was used to investigate the effects of the rhythmic prime in two other visual tasks, where instead of sentences, participants were shown shape sequences based on temporal hierarchy and shape sets based on spatial hierarchy, half of which with violations to their construction rules. Behavioural data (grammaticality judgements and reaction times) were collected from two groups of children, with and without musical training. According to our scientific hypothesis, children should perform better and faster after hearing the strong metrical prime than after hearing the weak metrical prime or silence, but only in the linguistic task and the visual task with shape sequences. Indeed, the task with spatially organized shape sets was the only left unaffected by the type of the prime, indicating as an important factor of this effect the relevance of temporal hierarchy and not the cognitive domain of the task. Moreover, children with musical training were more powerfully influenced by the type of the rhythmic prime compared to untrained children, positively by the strong metrical sequence and negatively by the weak metrical one compared to baseline (silence). The implications of this result in cross-domain structural representation understanding and music-based rehabilitation are highly significant.

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1. Introduction

1.1 Rhythm in language and music

Despite involving two different cognitive domains, language and music are both hierarchically organised, rule based systems which are dependent on how acoustic events unfold over time (Lerdahl & Jackendoff, 1983; Patel, 2010). Rhythm in both domains can be broadly defined as the temporal organisation of these events and has the ability to give rise to a sense of beat – a series of regular and recurrent psychological events – and metre – an emergent temporal structure that forms a hierarchical organisation of prominent and less prominent events (London, 2012).

In music, beat perception emerges from the periodicity of strong elements, whose hierarchical organization forms the basis of metre. For example, repetitions of a ternary metrical unit where a strong beat is followed by two weak ones (<u>1</u> 2 3 <u>1</u> 2 3 <u>1</u> 2 3) form the waltz rhythm. Our preference for metrical patterns is so strong that we automatically produce one even on hearing isochronous identical sounds (Bolton, 1894). Similarly, this alternation of strong and weak elements is found in speech, as stressed and unstressed syllables ("metric feet") and offers important prosodic information (Cason & Sch*ö*n, 2012). The term of stress can generally refer to intensity changes, but also changes in pitch and vowel duration. Speech rhythm has multiple levels of saliencies, such as different types (e.g. lexical, pitch, emphatic) and degrees of prosodic stress (Beckman & Edwards, 1994).

Based on dominant fluctuation rates, speech is comprised of three main temporal features: envelope, periodicity and fine structure, each one with distinct acoustic expressions, auditory and perceptual correlates and roles in linguistic contrasts (Rosen, 1992). Acoustic, neurophysiological and psycholinguistic analysis of natural speech demonstrates that there are organizational principles and perceptual units of analysis at very different time scales (Poeppel, 2003). Short-duration cues with a high modulation frequency, typically in ~30-50 Hz, involved with a crucial part of the signal fine-structure, correlate with elements at the phonemic level, such as formant transitions (differentiating /ba/ and /da/) and the coding of voicing (differentiating /ba/ and /pa/). In the next time scale, the acoustic envelope of speech closely correlates with syllabic rate and has a modulation spectrum typically peaking between 4-7 Hz. The transformation of the signal input into lexical and phrasal units that carry the intonation contour of an utterance is present at yet a lower modulation rate, roughly between 1-2 Hz. Although temporal modulations on these time-scales are aperiodic, they are rhythmic enough to provoke strong regularities in the time domain of speech (Giraud & Poeppel, 2012).

Though speech utterances are not as rhythmically regular as music (Patel, 2010), listeners may perceive stressed speech events to occur isochronously (Schmidt-Kassow & Kotz, 2009) and prosodic information is often repetitive, which allows it to be predictable (Dilley & McAuley, 2008). Recent research indicates the significance of the regular timing of stressed syllables (Kotz, Schwartze & Schmidt-Kassow, 2009; Quene & Port, 2005; Rothermich, Schmidt-Kassow & Kotz, 2012) and the syllable rate (Doelling, Arnal, Ghitza and Poeppel, 2014; Ghitza & Greenberg, 2009) for the processing of speech. Moreover, the entrainment to the speech rhythm appears to be beneficial to speech comprehension and reading skills in both children and adults (Ahissar et al., 2001; Giraud & Ramus, 2013). These findings suggest there is a preference for regularity in both speech and music and that this regularity may enhance the processing efficiency (Cason & Sch*ö*n, 2012).

Languages have developed different rhythms, grouped by phonetic research on rhythm into three categories, stress-timed, syllable-timed, and mora-timed (Abercrombie, 1967; Otake et al, 1993). English, German and Dutch are traditionally classified as stress-timed with consonants tending to cluster together, Spanish, French and Italian as syllable timed with a more balanced alternation of vowels and consonants, and Japanese as mora-timed. Many scientists have attempted to form rhythm metrics, formulas quantifying consonantal and vocalic variability in order to rhythmically classify languages (Ramus, Nespor & Mehler, 1999; Grabe & Low, 2002). The Greek language has an unclear classification. Greek remained unclassifiable according to Grabe and Low (2002), while other studies categorized it as syllable timed (Barry & Andreeva, 2001) or having a mixed rhythm (Baltazani, 2007). Diverging classifications of the less prototypical languages among the researchers rise doubts about the reliability of metrics (Arvaniti, 2009). The latter propose that less focus should be placed on timing or rhythmic types and more on the conception of rhythm that is based on grouping and patterns of prominence. She reports that an important difference between stress-timed and syllable-timed languages may be relevant to the spacing of prominences, not in terms of duration, but in terms of number syllables; thus, prominences may be sparser in syllable-timed languages. As Dauer (1983) has observed, the combination of relatively stable interstress intervals and different speaking rates suggests that languages like Greek, Spanish or Italian include more syllables in each interval. This difference could result in different rhythmic hierarchies and different degrees of flexibility in keeping prominences regular (Arvaniti, 2009).

Music, on the other hand, has generally been considered to have a more universal character, in the sense that some temporal processes may function in a similar manner irrespective of an individual's culture experience and exposure (Drake & Bertrand, 2001). Despite that, considerable cross-cultural influences on rhythm processing have been reported (Cameron, Bentley & Grahn, 2015).

In both domains metre is the key factor that allows a listener to form predictions about the timing of future events. According to Dynamic Attending Theory (DAT), these temporal expectations are formed by the synchronization, entrainment and phase coupling of internal neural oscillations to external auditory events (Jones & Boltz, 1989). It is proposed that this coupling modifies attention in time dynamically, with more attentional energy being allocated at most expected moments, i.e. strong metrical positions (Jones, 2010; London, 2012). As a result, auditory events that occur in most predictable moments are better processed. A similar model, the Attentional Bounce Hypothesis, is also proposed for speech, where the position of stressed syllables can be predicted on the bases of the metrical patterns of speech (Pitt & Samuel, 1990). Should this be the case, expectations induced by an external music stimulator can be hypothesized to impact on the processing of speech metre and, as a consequence, on the phonological processing of speech (Cason & Schön, 2012).

1.2 The contribution of musical rhythm to linguistic processing

The metrical prediction has no scale, as it considers only metrical relations, such as the number of expected elements and the stress pattern of their appearance, but not the exact durational expectations. Notably, temporal regularity and predictability of speech can enhance different aspects of linguistic processing, going from phoneme perception over lexical processing to syntax and semantic processing (Schön & Tillman, 2015). So, there are possible ways to investigate the effects of temporal regularity and predictability in music and speech processing in different experimental paradigms.

Phonological processing enhancement via rhythmic expectations can be shown with rhythmic speech cuing, where the metrical sequence is sort of a cue to the temporal structure of the following speech (Cason, Astésano, Schön, 2015). In these experiments reaction times are faster and greater phonological accuracy of spoken sentences is achieved in matching conditions compared to baseline and mismatching at several levels of phonological measurements (vowel, consonant, syllable and word production). The rhythmic priming of language processing is another experimental paradigm with typically longer stimulation that has not necessarily a “precise” temporal relation with the oncoming linguistic task. Successful metric processing and patterning serves as a framework enabling listeners to sequence linguistic input and build up syntactic hierarchies. Long-term rhythmic training is the third example of experimental design exploiting the similarities between musical rhythm and language processing. This type of design implies an active involvement with music and a long term intervention over several weeks, months or years.

Such experiments have already been successfully conducted in four languages: German, French, English and Hungarian. German speaking patients with basal ganglia injury (Kotz, Gunter & Wonneberger, 2005) and Parkinson’s disease (Kotz & Gunter, 2015) showed an improved performance on grammaticality judgements after being presented with a rhythmic prime with strong metrical structure. In French, Przybylski et al. (2013) tested typical and atypical (SLI, dyslexia) children and found their syntactic performance to be enhanced when preceded by metrically structured musical primes. Bedoin et al. (2016) reported similar findings in French typical and SLI children. Chern et al. (2018) showed the same effect with native English speaking children and Ladanyi et al. (2020) in Hungarian children with and without DLD. The effect was also found in young adults with and without dyslexia, who showed a larger ERP response to grammatical violations following regular vs. irregular primes (Canette et al., 2020).

A few studies tested the effect of rhythmic priming on phonological perception using a phoneme detection task in nonexistent words (Cason & Schön, 2012) and sentences (Cason, Astésano, & Schön, 2015). These studies employed the first paradigm (speech cuing) with the rhythm of the cues either matching or not matching the prosodic structure of the speech stimuli. Matching cues facilitated phonological processing compared to not matching cues extending the effect of rhythmic priming to phonemic perception. Furthermore, congenitally deaf children with cochlear implants were reported to improve the grammatical and phonological processing and sequencing of speech signals after a long-term training of regular musical primes (Bedoin et al., 2018). Rhythm has also been reported to be beneficial for stutterers, with marked reduction of stuttering when speaking to the pace of a metronome (Alm, 2004).

1.3 Neural correlates of linguistic and musical processing

The aforementioned effects have been attributed to potentially shared neural resources between language and music processing, especially syntax (Patel, 2003) and timing (Kotz & Schwartze, 2010; Kraus & Slater, 2016). Timing is fundamental to both and originates in evolutionarily primitive brain structures as the cerebellum (CE) and the basal ganglia (BG). While the primary function of the BG is linked to motor behaviour, some neurophysiologic theories assign temporal sequencing or the sequencing of general cognitive patterns to them (Kotz, Schwarze & Schmidt-Kassow, 2009; Kotz & Schmidt-Kassow, 2015). Also an extended sensorimotor network including these areas has been claimed to engage in the generation and perception of a beat structure in musical rhythm (Grahn & Brett, 2007; Grahn, 2009). If sequencing is closely linked to the perception of predictable cues (regular beats, meter, temporal chunks etc.), then syntactic processing should rely on the extraction of predictable cues in auditory language perception. Consequently, dysfunctional extraction of such cues in BG patients should then lead to secondary deficits in syntactic processing, as evidenced in behavioural and electrophysiological evidence (ERP) (Kotz, Frisch, von Cramon & Friederici, 2003; Kotz, Gunter & Wonneberger, 2005; Kotz, Schubotz, Sakreida & Friederici, 2006). Kotz, Schwartze and Schmidt-Kassow (2009) suggest that sequencing dysfunctions of the presupplementary motor area (SMA)-BG circuit may be compensated by increased influence of the cerebellar-thalamic-pre-SMA pathway. Kotz & Schwarze (2010) propose that a subcortico-cortical multifunctional network involving the CE and the BG aids temporal regularity extraction and expectation formation in sensory input, including music and speech processing. So speech has been proposed to exploit temporal structure, even if it is not regular, and temporal regularity to optimize comprehension.

Despite being presented sequentially, speech events are arranged in a hierarchical pattern, with one event determining another in the presence of the intervention of others. In 1951, Karl Lashley suggested that serial order in human behaviour, whether of language, music or performing a simple action, relies on the transition of spatially distributed memory representations into temporal sequence. This operation (can be attributed to syntax) requires temporary storage capacity for intermediate results and, according to his suggestion, it is implemented by central neural circuits that act as a "scannable buffer" by other circuits. This supraregular hierarchical sequence processing involves the activation of the left Inferior Frontal Gyrus (lIFG) that has been involved in syntactic operations by a wealth of neuroimaging data (Fiebach, Schlesewsky, Lohman, von Cramon & Friederici, 2005; Friederici, 2006). Musical syntax is reported to be also processed in Broca's area (Koelsch, 2006; Maess, Koelsch, Gunter & Friederici, 2001; Sammler, Koelsch & Friederici, 2011). Fitch and Martins (2014), revisiting Lashley, propose that cortical resources in the IFG, including at least BA 44 and BA 45, implement a storage buffer scannable by other cortical and subcortical circuits subserving sequential behaviour. Notably, this hypothesis allows for similar buffers to be implemented in regions other than the IFG, such as the hippocampus or the BG. Nonetheless, the involvement of Broca's area in the syntactic processing of music, language and mathematics is the core argument of Koelsch's Syntactic Equivalence Hypothesis (2012), developed by an initial idea of Patel (2003).

1.4 Rhythmic priming in non-linguistic visual fields

Chern et al. (2018) introduce two non-linguistic control tasks in order to explore whether the rhythmic priming effect should be attributed to a general effect of arousal on task performance or a more specific one deriving from shared neural mechanisms between music and grammar processing. The first was a math test, where a mix of visual and auditory items was used to assess counting, identifying numbers and solving simple problems. An obviously language-mediated example is provided by the authors ("How many are 3 apples and 4 apples?"), raising questions about the non-linguistic character of this condition. In the second task, described as visuo-spatial, children were asked to mark animal targets among non-animal ones. The problem of modality here is also of great importance. A prerequisite to accomplish an accurate comparison between two conditions would be to present their trials in a similar way, because the more differences between them we allow in our experimental design the more reasons/factors we end up with to account for our results. As Ladanyi et al. (in press) accurately comment, there should be a common design structure for all conditions with the same number of blocks, trials within the blocks and the way of presentation. The latter have chosen a non-verbal Stroop task to control for the grammaticality judgement condition, where arrows pointed towards the part of the screen they were placed at (congruent) or not (incongruent). This was more similar to the design of the linguistic task (thus more easily comparable) as it involved a sort of grammaticality judgements, but still irrelevant to the matter of sequencing and temporal hierarchy that seems to be of great importance to study the priming effect. Although they matched the procedures of them in many possible ways, still in the linguistic condition sentences were presented to the children auditorily whereas the other two visually. Children's response was also not matched, as they answered the linguistic and the picture naming task verbally but the non-verbal Stroop task by pressing a key. This difference can produce discrepancies in reaction time measurements, especially because the researchers had to proceed manually to avoid the problematic effect of naming studies with children's voice being too soft to activate the voice key.

But most importantly, even if the rhythmic priming effect is specific to grammar processing, its specificity to the linguistic and musical domain cannot be safely inferred. The linguistic processes that have been examined so far (Przybyltski et al., 2013, Chern et al., 2018, Ladanyi et al., in press) involve morpho-syntactic violations governed by higher syntactic operations. In a broader sense, syntax "denotes the organization of any combinatorial system in the mind." (Jackendoff, 2002) and can be described as a "set of principles governing the combination of discrete structural elements into sequences" (Patel, 2003). This hierarchical processing system has been proposed to extend to other cognitive domains, such as mathematics and action planning (Fitch & Martins, 2014; Koelsch, 2012; Lashley, 1951). As in this discussion only temporal hierarchy is involved, Fitch & Martins (2014) draw an enlightening comparison between hierarchical sequences and hierarchical sets. According to this, a good example of hierarchical sets could be a visuo-spatial part-whole hierarchy, in which certain elements contain others without any sequential ordering at each level, such as the schema of a face. On the other hand, when sequential order matters, we have hierarchical sequences, as in language and music, where different order arrangement represents separate concepts.

1.5 The current study

Framed by a large literature, we have set multiple experimental goals. First, we have tried to determine if rhythmic priming enhances grammaticality judgements also in Greek typically developing children. As noted above, Greek has not a clear rhythmic classification as opposed to other languages, in which the rhythmic priming experimental design has already been reported successful, such as German and English, classified as prototypical stress-timed languages, and French, categorized as syllable-timed. If Greek is indeed closer to syllable-timed languages in the spectrum of rhythmic classification, then it would be plausible to expect that the prime with the strong rhythmical pattern will enhance the grammaticality judgements of the children, as reported in French. This rhythmic sequence has a strong metrical structure of repeated, regularly reoccurring accents, thus, it provides systematic grouping and facilitates perception, analysis and prediction. It has to be considered that this is a very frequent metrical pattern in western music (similar to common time), which implies higher expectancy levels in countries of the Western Europe. On the contrary, the other sequence has a weaker metrical structure involving pauses on several beats including the first one, more beat-level syncopations, greater division of time values, asynchrony between the main rhythmic line and the according (less frequent simultaneous presentations). Based on its characteristics, this type of music is much more difficult to act as framework helpful in forming expectations about oncoming events. Thus, we expect that Greek-speaking children will perform better in grammaticality judgements after hearing to the strongly metrical sequence as opposed to the weak one in line with the rhythmic priming theory.

Furthermore, we added in our experimental design an extra sound condition of silence. In this way, we intended to ensure that it is the strong metrical sequence enhancing the grammatical skills of the children and not the weak one deteriorating them. Previous studies have compared only between two auditory conditions, reported as regular vs irregular (Chern et al., 2018; Przybylski et al., 2013) and regular vs non-rhythmical environmental sound scene (Bedoin et al., 2016). Although, the latter reported bigger rhythmic priming effect between the strongly metrical sequence comparing with the weak one than with the non-rhythmical sound, Ladanyi et al. (2020) found no significant difference between the weak metrical sequence and the baseline sound. The latter attributed this finding to a possible difference between the impact of environmental noise compared to that of silence and consider the non-significance as evidence of the non-detrimental effect of the weakly metrical prime. We further investigated this finding expecting to find similar performance in the weak metrical prime and the baseline condition of silence.

Our second goal was to investigate if rhythmic priming is domain general or extends to other cognitive fields. In our study we explore whether the rhythmic priming effect, as a process of sequential hierarchy applicable to both language and music, can extend to the visual domain or is a well-defined specific capacity. To accomplish that we have designed two visual non-verbal (and non-linguistic to the extent it is possible when thought is involved) tasks, one with a temporal and one with a spatial hierarchy. In the first task, trials consisted of grammatical and ungrammatical geometric shape sequences of 3 basic geometries: blue rectangle, yellow triangle, red circle. This kind of stimuli has been used before to test implicit learning in TD primary school children (9-12 years old) and children with developmental dyslexia (Pavlidou, Williams and Kelly, 2009). In the second task, geometrical shapes were ordered hierarchically in space forming two-dimensional patterns, governed by a set of combinatorial principles forming multiple hierarchical levels, as described in a series of experiments in Westphal-Fitch et al. (2012). Children of fifth grade in Greek primary schools are taught both geometrical shape sequences and sets in the class of mathematics, so they were all familiar with the concept. According to Fitch & Martins (2014) we expect to find rhythmic priming effect only in the shape sequences condition that temporal hierarchy is involved, and not in the geometric sets condition. In this way, we can demonstrate that the effect is not specific to speech/language processing, but to grammar processing in a domain-general sense.

Our third goal was the maximum possible match between conditions. All three tasks were presented visually after the primes, with numbers of blocks and trials absolutely balanced between them. In each condition, children were making judgements (between "ok"/"fine"/"good" and "not ok"/"poor"/"bad"), always responding by pressing the relevant key. Visual presentation of linguistic stimuli in a similar experimental paradigm has been previously attempted with success. The DAT has been empirically explored in cross-modal perceptual setups to test for interactions with visual perception. The effect of auditory rhythmic expectation can enhance the detection of visual targets, both images (Escoffier, Sheng & Schirmer 2010) and words in a lexical detection task (Brochard, Tassin & Zagar, 2013) when presented on the beat. In a more relevant study, college students performing a visual word recognition task showed an increased negative ERP effect elicited by mismatching stress patterns, i.e. when the rhythmic structure of the auditory prime was not consistent to the rhythm of the word (Fotzidis et al., 2018). Similar negative responses have been found when the metrical structure of the spoken target word did not match the rhythmic structure of the musical prime (Cason & Schon, 2012). This is the first time to our knowledge that the rhythmic priming effect will be explored with stimuli of visually presented whole sentences (reading). To preserve the effect of the prime in time, we included only 5 trials (4 experimental trials and 1 filler) in each block (as opposed to 6 in Przybylski et al., 2013 and 10 in Landanyi et al., 2020) with 32s prime duration, so that there would be time for the children to read each sentence and respond before the effect could fade out. We expect that the visual presentation of our stimuli will not affect the appearance of the rhythmic priming effect.

Our last goal was to confirm that syntactic abilities are closely related to rhythmic and musical abilities in young children. Abilities in rhythm perception have been reported to be associated with morpho-syntactic abilities in speech production (Gordon, Shivers et al., 2015) and musically trained children show better morpho-syntactic abilities than non-musically trained children (Jentschke & Koelsch, 2009). In Fotzidis et al. (2018), musical rhythm aptitude was a statistically significant predictor of speech rhythm sensitivity, even after controlling for reading comprehension skills. This is in line with previous ERP studies showing that adult musicians performed better than non-musicians at detecting words pronounced with an incorrect stress pattern (Marie, Magne & Besson, 2011). Since almost half of our participants (12/25) have received music training for two consecutive years or more, we will compare their results expecting to find better performance after strongly metrical primes in musically trained children. RT data were also collected from all tasks and conditions. These data can provide useful information about the priming effect and its implications, especially when ceiling effect is observed in performance.

2. Methods

2.1 Participants

Thirty native Greek-speaking children (11 males) aged 10 to 11 years (M=10.44, SD=0.26) participated in this study. Parents gave informed consent and children gave verbal assent. Parents reported no concerns about cognitive, motor, emotional, sensory or language development of their children. Participants were recruited from 4 primary schools of Dionysos Municipality in northeastern Attica, Greece. All children scored greater than 85% on all relevant subtests (Morphology Production, Morphosyntactic Comprehension and Recall) of the Diagnostic Verbal IQ Test for School Age Children (Stavrakaki & Tsimpli, 2000). Non-verbal IQ was in normal range (M=0.84, SD=0.10) on the RAVEN's Coloured Progressive Matrices (CPM) test (Raven et al., 1998). Hearing was screened by pure-tone testing and all participants were found to have normal hearing. Gender and music experience of were reported and assessed. In particular, children that have received formal music education for two consecutive years or more were classified as musically trained (12/25). In a similar way, parents reported their education, profession and economic status and two groups were formed by the experimenter (Table 1). Study data were collected, managed and stored using Psychophysics Toolbox Version 2 (PTB-2) in Matlab R2017b.

PARTICIP.	GENDER	AGE	MUSIC	RAVEN	DVIQ			
					PROD.	COMPR.	RECALL	TOTAL
1	M	10.75	√	.88	.85	.85	1.0	.86
2	M	10.45	X	.67	.91	.73	.90	.85
3	M	10.45	X	.58	.97	.82	1.0	.93
4	M	10.08	X	.94	1.0	.91	1.0	.97
5	F	10.25	X	.92	.99	.97	1.0	.98
6	F	10.67	X	.88	.96	.94	1.0	.95
7	F	10.33	√	.86	.87	.85	1.0	.86
8	F	10.38	√	.92	.97	.97	.90	.96
9	M	10.30	√	.78	.91	.85	.90	.89
10	M	10.45	X	.88	.94	.88	1.0	.93
11	F	10.54	√	.94	.96	1.0	1.0	.97
12	F	10.45	√	.64	.99	.88	1.0	.95
13	M	10.75	√	.97	1.0	.94	1.0	.98
14	F	10.08	X	.69	.97	.91	.90	.95
15	*F*	*10.75*	*√*	*.86*	*.97*	*.97*	*1.0*	*.97*
16	*F*	*10.67*	*X*	*.80*	*.96*	*.97*	*1.0*	*.96*
17	F	10.17	X	.83	1.0	.97	.90	.98
18	F	10.60	√	.94	.93	.91	1.0	.93
19	F	10.08	√	.83	.97	.85	.80	.92

20	F	10.04	√	.88	.97	.94	1.0	.97
21	F	10.17	X	.78	.87	.85	1.0	.86
22	M	10.54	X	.86	.91	.88	.90	.90
23	F	10.50	X	.97	.99	.94	1.0	.97
24	M	10.83	X	.72	.85	.85	1.0	.86
25	*M*	*10.50*	*X*	*.83*	*.96*	*.94*	*1.0*	*.95*
26	F	10.58	√	.94	.94	.94	1.0	.95
27	F	10.58	X	.88	.94	.91	1.0	.94
28	M	10.50	√	.92	.93	1.0	1.0	.95
29	F	10.92	X	.83	.97	1.0	1.0	.98
30	*F*	*10.83*	*X*	*.88*	*1.0*	*1.0*	*.90*	*.99*

Table 1. Descriptive data per participant

2.2 Material

2.2.1 Musical Stimuli

Stimuli consisted of the same two 32-s musical sequences from Przybylski et al. (2013), containing similar number of tones but different in rhythmic structure (Figure 1). Both rhythms consisted of regular repeated patterns written in 4-4 time and performed by percussion instruments. Regularity and repetition are fundamental prerequisites for a sound sequence to be characterized as rhythmical. The differences of the two musical sequences are then to be found within the metrical structure. The first sequence had a strong metrical structure consisting of an onset on the first pulse (down beat) followed by three weaker beats of different time values (dotted-quarter, eighth, quarter). This simple structure of repeated, regularly reoccurring accents provides systematic grouping and facilitates perception, analysis and prediction. On the contrary, the second sequence has a weaker metrical structure involving pauses on several beats including the first one, more beat-level syncopations, greater division of time values, as well as asynchrony between the main rhythmic line and the according. All these characteristics lead to a much more complex structure of unaccented or unequal distanced notes, hard to comprehend and predict. There is also a third condition of silence that lasts also 32s and controls for children's performance in a non-rhythmic environment.

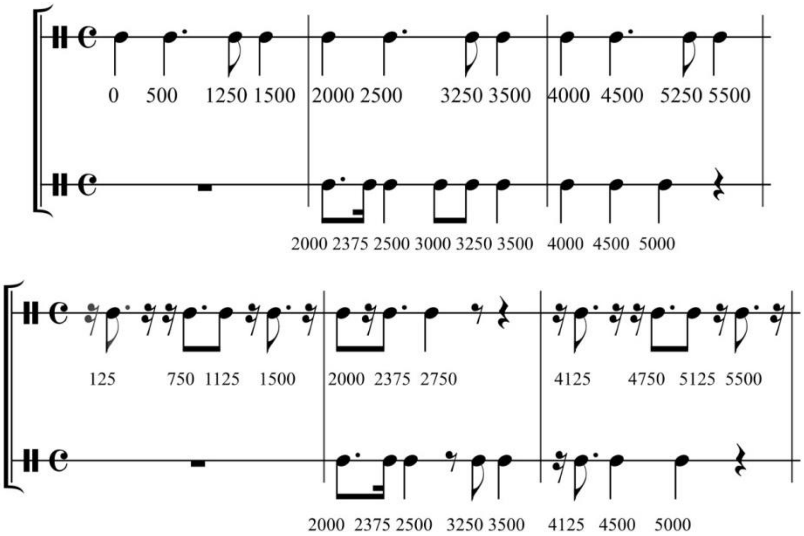

Figure 1. Musical score of the beginning of the strongly metrical prime (top) and the weakly metrical prime (bottom).

2.2.2 Linguistic Stimuli

Material was composed of 49 sentences in total. Two experimental conditions were assessed, grammatical (18) and non-grammatical (18). In addition 9 control sentences/fillers and 4 practice items were included. The grammatical condition involved sentences with gender agreement between a noun and an adjective, while the non-grammatical condition involved sentences with gender violations in the adjective-noun agreement with 6 masculine, 6 feminine and 6 neutral nouns in each condition (grammatical, non-grammatical). Nouns and adjectives in Greek can have many different suffixes (see Ralli, 1994), which can be typical/common for masculine (-ος), feminine (-η or -α) or neutral (-ο) gender (see Anastasiadi-Simeonidi & Chila-Markopoulou, 2003; Ralli, 2002; Tsimpli & Mastropavlou, 2011; Varlokosta, 2011, 2019); hence facilitate or impair detecting a violation, when occurring. For example, when a feminine noun with a masculine ending such as "έρημος" (desert) is incorrectly preceded by an adjective with a masculine ending "απέραντος έρημος" (vast desert), a child can be disoriented.

Sentences were controlled so that the number of disagreeing suffixes within each gender group was balanced among the other 2 genders. For example, in the non-grammatical condition with feminine nouns, there were adjectives with typical masculine ending (e.g. "πλούσιος χώρα": wealthy country) and also with typical neutral (e.g. "λεπτό άμμο": thin sand). The same held for the other two groups of non-grammatical sentences.

The 18 grammatical sentences were different from the 18 non-grammatical ones, but there was a correspondence in the type of the adjective and noun. For example, the noun phrase "απέραντ**η** έρημ**ος**" was used incorrectly in the sentence "Τα πάντα καλύπτονται από απέραντο έρημο." and had the grammatical equivalent "Το κατάτημα με τα κοσμήματα έχει μυστικ**ή** είσοδ**ο**": So each sentence was heard only once.

In the 4 practice trials (2 grammatical & 2 non-grammatical) the disagreement was more salient, in order to ensure that the child understands the kind of problem presented. The fillers were 9 simple grammatically correct sentences with form completely irrelevant to the experimental task, aiming to control for the children's attention. All 49 sentences consisted of 8 words. In the linguistic task, 4 sentences had to be removed because they were repeatedly mistaken with subsequent verbal reports indicating ignorance ("Ο γαμπρός περιμένει στην εκκλησία τη μέλλοντα νύφη.") or displeasure with article omission ("Η Ελένη αγόρασε ωραία φούστα για τη γιορτή.").

Each sentence was presented in the middle of the screen written in Arial 16 black letters against white background. The file format used was JPEG and the managing program Adobe Photoshop CC 2015.

Experimental Paradigm: There were 9 blocks of linguistic stimuli in total, each one preceded by a 32s priming auditory sequence: 3 by the simple one with strong sense of metrical structure, 3 by the complicate one with weak sense of metrical structure, and 3 by silence. The 9 auditory stimuli were presented in random order before each block. Each block consisted of 5 sentences (4 experimental and a filler), with a total of 45 sentences across 9 blocks. The sentences were randomly presented without an even distribution of grammatical and non-grammatical within each block (to avoid learning effects).

2.2.3 Shape Grammars I: Geometric shape sequences (Temporally Ordered)

Material was composed of 49 shape sequences of 3 basic geometries: blue rectangle, yellow triangle, and red circle. Two experimental conditions were assessed (Table 2), grammatically correct (18) and grammatical violation (18). In addition, 9 control sequences and 4 practice sequences were included.

Each correct sequence had an equivalent violation sequence; they were presented in a pseudo-random order so that each block could have either the correct or the incorrect form. All stimuli consisted of 8 shapes; the first four forming a subsequence that had to be repeated in the last four shapes for the overall sequence to be grammatical.

Each 4-element first subsequence was created according to 6 different patterns: 1. “A-B-A-C”, 2. “B-A-C-A”, 3. “A-B-C-A”, 4. B-A-A-C”, 5. “B-C-A-A”, 6. “A-A-B-C”, where a blue rectangle, a yellow triangle and a red circle were used instead. There were 3 alternatives for each pattern, one starting with each of 3 shapes. In this way every shape was used equal times as the others (95), each sequence started equal times with each shape (12), each shape appeared equal times in each position. The error could always be found in the last shape, that was either consistent to the rule or not. In the 18 incorrect sequences, the 3 shapes were equally placed in the last position to break the rule.

The rule had to be deduced by the 4 practice trials (2 correct and 2 incorrect) which were easier to perceive because they had only 2 alternating shapes, forming sequences of 2 types: 1. “A-B-A-B-A-B-A-B “, 2. “A-A-B-B-A-A-B-B”; the error found in the last shape as well.

The 9 filler sequences were also all correct and much easier to handle. There were 3 patterns used: 1. “A-B-A-B-A-B-A-B “, 2. “A-A-B-B-A-A-B-B”, 3. “A-A-A-B-A-A-A-B”, for each one of the 3 shapes, where 2 forms of the same shape, one filled and one void, alternated. The experimental paradigm was exactly the same as in the aforementioned condition.

		basic unit circle	basic unit rectangle	basic unit triangle
RULE 1	GR	● ■ ● ▲ ● ■ ● ▲	■ ▲ ■ ● ■ ▲ ■ ●	▲ ● ▲ ■ ▲ ● ▲ ■
	UN	● ■ ● ▲ ● ■ ● ■	■ ▲ ■ ● ■ ▲ ■ ▲	▲ ● ▲ ■ ▲ ● ▲ ●
RULE 2	GR	● ● ▲ ■ ● ● ▲ ■	■ ■ ▲ ● ■ ■ ▲ ●	▲ ▲ ■ ● ▲ ▲ ■ ●
	UN	● ● ▲ ■ ● ● ▲ ●	■ ■ ▲ ● ■ ■ ▲ ■	▲ ▲ ■ ● ▲ ▲ ■ ▲
RULE 3	GR	● ▲ ■ ● ● ▲ ■ ●	■ ● ▲ ■ ■ ● ▲ ■	▲ ■ ● ▲ ▲ ■ ● ▲
	UN	● ▲ ■ ● ● ▲ ■ ▲	■ ● ▲ ■ ■ ● ▲ ●	▲ ■ ● ▲ ▲ ■ ● ■
RULE 4	GR	▲ ● ● ■ ▲ ● ● ■	● ■ ■ ▲ ● ■ ■ ▲	■ ▲ ▲ ● ■ ▲ ▲ ●
	UN	▲ ● ● ■ ▲ ● ● ▲	● ■ ■ ▲ ● ■ ■ ●	■ ▲ ▲ ● ■ ▲ ▲ ■
RULE 5	GR	■ ▲ ● ● ■ ▲ ● ●	▲ ● ■ ■ ▲ ● ■ ■	● ■ ▲ ▲ ● ■ ▲ ▲
	UN	■ ▲ ● ● ■ ▲ ● ■	▲ ● ■ ■ ▲ ● ■ ▲	● ■ ▲ ▲ ● ■ ▲ ●
RULE 6	GR	■ ● ▲ ● ■ ● ▲ ●	▲ ■ ● ■ ▲ ■ ● ■	● ▲ ■ ▲ ● ▲ ■ ▲
	UN	■ ● ▲ ● ■ ● ▲ ■	▲ ■ ● ■ ▲ ■ ● ▲	● ▲ ■ ▲ ● ▲ ■ ●

Table 2. Experimental items for the hierarchical sequences task.

2.2.4 Shape Grammars II: Geometric shape sets (Spatially Ordered)

Material was composed of 49 shape sets. Two experimental conditions were assessed, grammatically correct (18) and grammatical violation (18). In addition, 9 control sequences and 4 practice sequences were included.

Shape sets were formed as an extension of formal language theory's linear sequences or strings to two-dimensional patterns (Fitch & Martins, 2014). All visual plane patterns were generated based on an array of (6x6) 36 smaller units, governed by a set of combinatorial principles –grammars– that constrained their arrangement into groups of multiple hierarchical levels, as described in the "Spot the flaw" series of experiments in Westphal-Fitch et al. (2012).

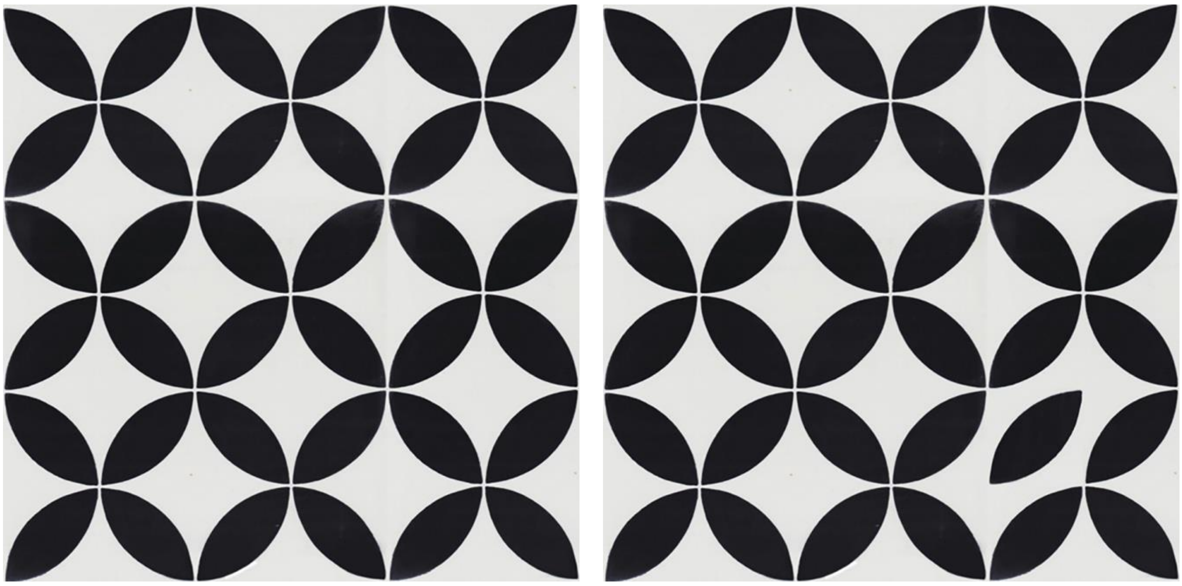

Figure 2. Example of a grammatical (right) and an ungrammatical (left) item of hierarchical sets task.

The type of violation used in this study was orientation flaws in hierarchical grouped rotation patterns with tiles horizontally, vertically or diagonally symmetrical. The locations of the (18) flaws were equally distributed (3) in each column and (3) in each row of the 6x6 board, but also balanced across quartiles, as seen in Table (3). Each correct set had an equivalent violation set; they were presented in a pseudo-random order so that each block could have either the correct or the incorrect form.

	1	**2**	**3**	**4**	**5**	**6**
a	Sets_13_False		Sets_6_False		Sets_11_False	
b	Sets_5_False	Sets_17_False		Sets_2_False		Sets_4_False
c		Sets_8_False		Sets_16_False		*Pract_2_False*
d		*Pract_1_False*	Sets_15_False		Sets_14_False	Sets_18_False
e	Sets_3_False			Sets_9_False	Sets_1_False	
f		Sets_7_False	Sets_10_False			Sets_12_False

Table 3. Flawed spots balanced over columns, rows & quartiles.

Once again, the 4 practice trials (2 grammatical and 2 non-grammatical) were easier to perceive less complex structures, highly typical of the underlying rule, so that children would be facilitated to deduce it. The 9 filler sets were also 36-unit, all grammatical patterns of structured repetition of simple geometric elements in a two-dimensional plane. The experimental paradigm was exactly the same as in the aforementioned conditions.

2.3 Procedure

Testing was presented to the children as a computer game. Each condition started with the 4 practice trials including visual stimuli with a. sentences, b. temporally ordered hierarchical sequences and c. temporally unordered hierarchical sets. The order was different for each child, so that all combinations were equally frequent. Children were asked to observe the image shown on the screen and decide whether it was “ok”/”fine”/”good”, thus written/drawn by a nice green dragon to assist them or if it was “not ok”/”poor”/”bad” and written/drawn by a naughty red dragon to trick them into losing the game. Words like “correct-incorrect” and “right-wrong” were avoided in order to let children realize the rule-based nature of the task on their own. Selection was made by pressing the arrow key -right if correct and left if wrong- that pointed on the corresponding carton-made dragon placed on each side of the screen. Feedback was automatically provided on the screen after each response and, if wrong, the child was asked to justify the given answer and helped to understand the error.

Once the practice trials were completed and the children had deduced the underlying rules of the task, the experimental phase began. For each block, children were asked to listen to the music -or silence- while being shown a drum -or a silenced drum- symbol on the screen. After 32-s the auditory primer was over and automatically a visual stimulus (sentence, sequence or set; depending on the experimental condition) was presented on the screen. Children had no time restriction to make their judgements. Once they had pressed the button of their choice (left or right arrow; all other keys were disconnected during the procedure), the next image was automatically presented without providing any feedback. After presenting 5 visual stimuli, the block was completed and the auditory stimulus was again presented for a total of 9 blocks. This exact procedure was repeated 3 times, one for each task. All participants completed all tasks and then answered a general demographic questionnaire enriched by questions about their family/personal music education/preferences. On completion of each task, children were asked to assess one more time their incorrect trials and, if erred again, they were asked to justify their answers. In this way, errors made for reasons irrelevant to the experimental purpose (e.g., ignorance) could be located and excluded from the analysis.

The experimental procedure took place in a quiet place of the house of each child. Each child received a small toy when the total procedure was over (girls received stickers and boys toy planes). An HP Pavilion Power (model 15-cv005nv) laptop was used for this purpose. Sounds were presented over wired caps on ear headphones manually calibrated to comfort levels (around 70 dB).

3. Data Analysis

Performance of grammaticality judgements was subjected to a signal detection analysis, in line with current literature (Chern et al., 2018; Ladanyi et al., 2020; Przybylski et al, 2013;). In this analysis, the proportion of hits (p[hits]), which include the correct responses for ungrammatical trials, and the proportion of false alarms (p[Fas]), which include the errors for grammatical trials, were assessed after strongly metrical, weakly metrical and silence primes. Discrimination sensitivity and response bias were calculated for each participant and each prime condition. *d'* is defined as z(p[hits]) – z(p[Fas]) and response bias *c* as –0.5[z(p[hits])+z(p[Fas])] (Macmillan & Creelman, 2005; note also the typographical error in Przybylski et al., 2013). In order to calculate *d'* and *c*, hit and false alarm rates of zero or one were substituted with 0.99 and 0.01 respectively. This was usual in our data because, in order to exclude factors other than the primes, such as ignorance or difficulty, we used easy-to-process trials and faced ceiling effect in all tasks. Fillers were calculated and controlled for children's attention. Children (N=3) that missed 20% or more of the fillers in a task were excluded from the analysis as inattentive. For each task (language, shape sequences, shape sets), *d'* and *c* were analysed by two repeated measures analyses of variance (RM ANOVAs, mixed factorial design) with musicality (children with musical training, children without musical training) as the between-participants factor and musical prime (strongly metrical, weakly metrical, silence) as the within-participant factor. To estimate effect sizes, we calculated partial η^2 (Cohen, 1973).

Analyses on RT data were performed for correct trials only. For each participant, outlier responses were removed from data (RTs which were +/–2.5 x S.D. from the mean). Children (N=1) with means in one or more conditions greater than 14s (the double of the average mean of all conditions) were excluded from the analysis. To analyse RTs, three repeated measures analyses of variance (RM ANOVAs, mixed factorial design) was used, one for each task (language, shape sequences, shape sets), with musicality as a between-subjects factor (children with musical training, children without musical training) and musical prime (strongly metrical, weakly metrical, silence) as the within-participant factor.

4. Results and Discussion

4.1 Linguistic Task

For d' (see Figure 3, Table 4) the interaction of the factors music prime and musicality was marginally significant, F (2, 48) = 2,72, p = .076, partial η^2 = .10. The main effect of the musical prime was also marginally significant, F (2, 48) = 2,87, p = .067, partial η^2 = .11, whereas the main effect of musicality was not statistically significant, F (1, 24) = 1,39, p = .25, partial η^2 = .06. As expected, all children performed better after the strongly metrical prime condition compared to baseline (MD= .49, p = .029) and also to the weakly metrical prime (MD = – .34, p = .095), even though this difference was also marginally significant. The contrast between silence and the prime with weak metrical structure was not significant (MD = – .15, p = .51).

	Average *d'*			***SE***		
Group	Strongly Metrical Prime	Weakly Metrical Prime	Silence (Baseline)	Strongly Metrical Prime	Weakly Metrical Prime	Silence (Baseline)
Language						
Trained	4.38	3.56	3.67	.20	.27	.28
Not Trained	4.20	4.35	3.94	.19	.25	.26
Total	4.29	3.95	3.81	.14	.19	.19
G. Sequences						
Trained	4.21	3.43	3.70	.23	.31	.31
Not Trained	3.85	3.68	3.66	.21	.29	.28
Total	4.02	3.56	3.68	.15	.21	.21
G. Sets						
Trained	3.37	3.83	3.24	.33	.27	.39
Not Trained	3.06	3.07	3.16	.30	.25	.36
Total	3.20	3.42	3.20	.22	.18	.27

Table 4. *d'* Data Pattern of the experiments with language, geometrical sequences and geometrical shapes averaged over participants, by musical prime (Strongly Metrical, Weakly Metrical, Silence).

Then, pairwise comparisons were drawn to investigate the simple effects of the prime condition on the two groups of different musicality levels. Children without a musical background showed a general benefit of both rhythms compared to silence, but this pattern did not reach significance. On the contrary, children with musical training presented a clear pattern with the strongly metrical prime leading to significantly better performance as opposed to silence, F (1, 24) = 2.31, p = .03, partial η^2 = .09 and the weakly metrical prime, F (1, 24) = 2.88, p = .01, partial η^2 = .11. Most importantly, the only prime condition with significant difference in *d'* between the two groups was that of the weakly metrical prime, with the musically trained performing worse than the children without music education, F (1, 24) = 2.13, p = .04, partial η^2 = .08. This finding suggests that a non-metrical prime can hinder linguistic performance of subjects with a good rhythmic understanding.

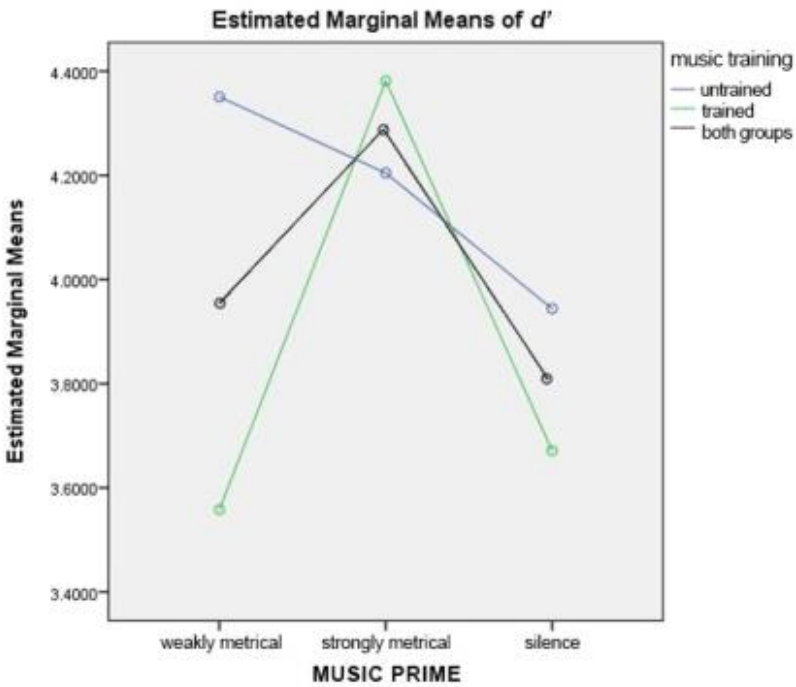

Figure 3. *d'* plot averaged over participants, by musical prime (Strongly Metrical, Weakly Metrical, Silence) in the linguistic task.

The analysis of *c* (see Table 5) showed that the rhythmic priming effect found in the linguistic task performance was not accompanied by a difference in response bias. The main effect of prime was not significant, p = .90, neither the main effect of musicality, p = .85, nor their interaction, p = .61. We should note though that the negative values of the means presented indicate that the children were mildly conservative in their judgements.

Group	**Average *c***			***SE***		
	Strongly Metrical Prime	Weakly Metrical Prime	Silence (Baseline)	Strongly Metrical Prime	Weakly Metrical Prime	Silence (Baseline)
Language						
Trained	-.02	-.06	-.09	.11	.13	.14
Not Trained	-.13	-.05	.06	.10	.12	.13
Total	-.08	-.05	-.01	.08	.09	.09
H. Sequences						
Trained	-.22	-.09	-.48	.14	.17	.15
Not Trained	-.01	-.19	-.27	.13	.15	.14
Total	-.11	-.14	-.36	.11	.10	.10
H. Sets						
Trained	.12	-.05	.33	.13	.17	.15
Not Trained	-.44	-.34	-.18	.12	.15	.14
Total	-.18	-.21	.06	.09	.11	.10

Table 5. *c* Data Pattern of the experiments with language, geometrical sequences and geometrical shapes averaged over participants, by musical prime (Strongly Metrical, Weakly Metrical, Silence).

For the RTs (see Table 6, Figure 4) in the linguistic task, there was no interaction between musical prime and musicality, F (2, 48) = 0.63, p = .54, partial η^2 = .03 and the main effect of the latter was not statistically significant, F (1, 24) = 0.41, p = .53, partial η^2 = .02, even though musically trained children appeared to respond faster in all prime conditions. Moreover, musical prime was again marginally significant, F (2, 48) = 2.86, p = .067, partial η^2 = .11, with all children being faster after the strongly metrical prime compared to the weakly metrical one, (MD= .49, p = .01) and to baseline, even though this difference was not statistically significant (MD= .07, p = .79). As presented in Figure 4, musically trained and untrained children responded marginally faster after hearing to the strongly metrical prime in comparison to the weakly metrical, F (1, 24) = 1.94, p = .06, partial η^2 = .08 and F (1, 24) = 2.02, p = .06, partial η^2 = .07, respectively. Nevertheless, children with musical background performed faster after the strongly metrical prime compared to silence without this difference being statistically significant (MD= .33, p = .41). Moreover, children without music education showed slightly slower RTs after the silence condition comparing to the strongly metrical prime (MD= .18, p = .62).

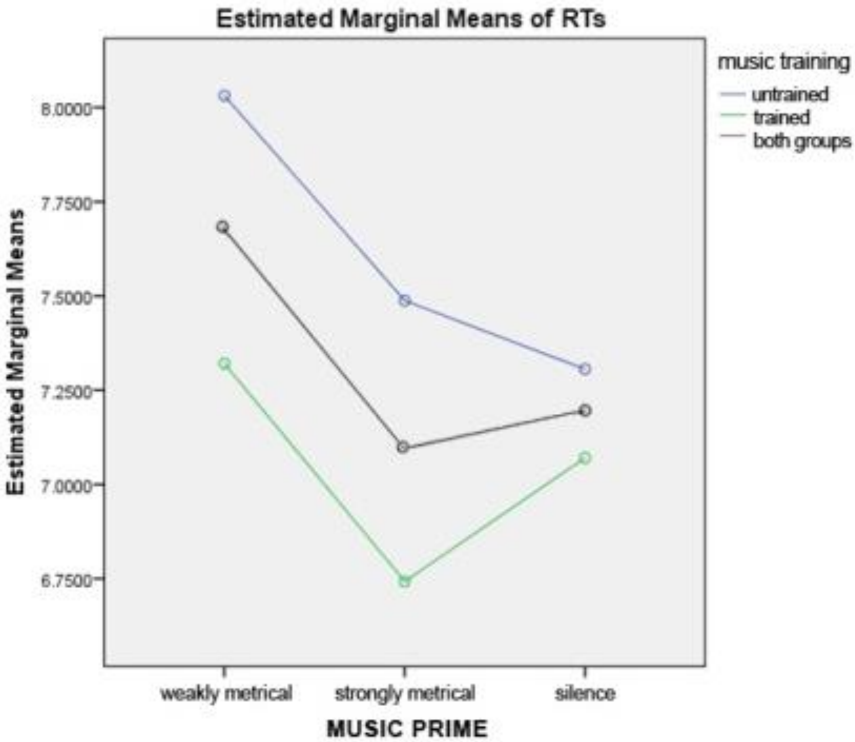

Figure 4. RTs plot averaged over participants, by musical prime (Strongly Metrical, Weakly Metrical, Silence) in the linguistic task.

Thus, comparing to baseline we could say that only musically trained children received a small temporal gain from the strongly metrical prime, whereas all children seem to have suffered from the weakly metrical prime in their reaction times.

Group	**Average *RTs***			***SE***		
	Strongly Metrical Prime	Weakly Metrical Prime	Silence (Baseline)	Strongly Metrical Prime	Weakly Metrical Prime	Silence (Baseline)
Language						

Trained	6.74	7.32	7.07	.65	.73	.66
Not Trained	7.49	8.03	7.31	.60	.68	.61
Total	7.14	7.70	7.20	.45	.50	.45
H. Sequences						
Trained	6.55	7.15	7.19	.45	.57	.51
Not Trained	5.90	6.47	6.64	.41	.53	.48
Total	6.20	6.79	6.89	.31	.39	.35
H. Sets						
Trained	7.63	8.10	7.40	1.04	1.03	.98
Not Trained	8.09	7.56	8.34	.96	.96	.91
Total	7.88	7.81	7.90	.71	.70	.66

Table 6. *RTs* Data Pattern of the experiments with language, geometrical sequences and geometrical shapes averaged over participants, by musical prime (Strongly Metrical, Weakly Metrical, Silence).

In sum, all children presented reaction times and performance patterns considerably aligned to the current literature, i.e. better general processing ability after listening to the strongly metrical prime contrasted to the weakly metrical and baseline. Musically trained children seemed to comply more with our theoretical frame, whereas children lacking a musical background were generally benefitted by the presence of a prime, independently of its rhythmical characteristics.

4.2 Shape Sequences Task

For the *d'* in the shape sequences task (see Figure 5, Table 4), there was no interaction between musical prime and musicality, F (2, 48) = 0.83, p = .44, partial η^2 = .08 and the main effect of the latter was not statistically significant, F (1, 24) = 0.04, p = .85, partial η^2 = .001. The musical prime though was close to marginally significant, F (2, 48) = 2.20, p = .12, partial η^2 = .08, with all children performing better after the strongly metrical prime compared to the weakly metrical one, (MD= .48, p = .03) and to baseline (MD= .35, p = .14), even though this difference was also non-significant. In particular, children with music training performed better after hearing the strongly metrical prime compared to the weakly metrical prime, F (1, 24) = 2.51, p = .02, partial η^2 = .10 and to baseline, F (1, 24) = 1.48, p = .15, partial η^2 = .06, even though this contrast did not reach significance either. The performance pattern of the children without musical training was similar, but the differences between prime conditions were not statistically significant. Our data suggest that the musically trained children were more benefitted by the strongly metrical prime than the children without music education (MD= .36, p = .25), but also more harmed by the weakly metrical one (MD= .25, p = .56), even though these contrasts were not significant either.

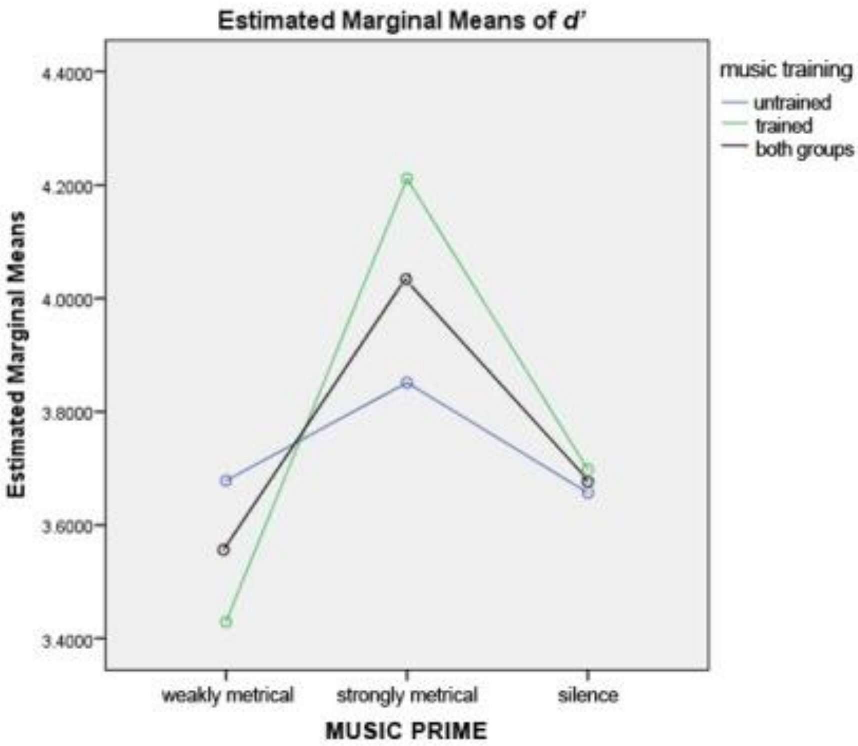

Figure 5. *d'* plot averaged over participants, by musical prime (Strongly Metrical, Weakly Metrical, Silence) in the geometric sequences task.

The analysis of *c* (see Table 5) showed that the rhythmic priming effect found in the sequence task performance was not accompanied by a difference in response bias.

The main effect of prime was close to marginally significant, F (2, 48) = 2.27, p = .11, partial η^2 = .09, but not the main effect of musicality, p = .45, nor their interaction, p = .42. All children were shown again to be slightly conservative in their judgements, but gave more negative responses (judgements of trials as non-grammatical) when silence was preceded compared to both the strongly metrical, F (1, 24) = 1.85, p = .076, partial η^2 = .07, and the weakly metrical prime, F (1, 24) = 1.98, p = .058, partial η^2 = .08.

For the RTs in the shape sequences task (see Figure 6, Table 6) there was no interaction between musical prime and musicality, F (2, 48) = 0.03, p = .98, partial η^2 = .001, and the main effect of the latter was not statistically significant, F (1, 24) = 1.07, p = .31, partial η^2 = .04. But, the main effect of musical prime was found statistically significant, F (2, 48) = 3.13, p = .05, partial η^2 = .12, as responses after hearing the strongly metrical prime were faster in comparison with baseline (MD=.69, p = .01) and with the weakly metrical prime (MD= .59, p = .07) in both groups.

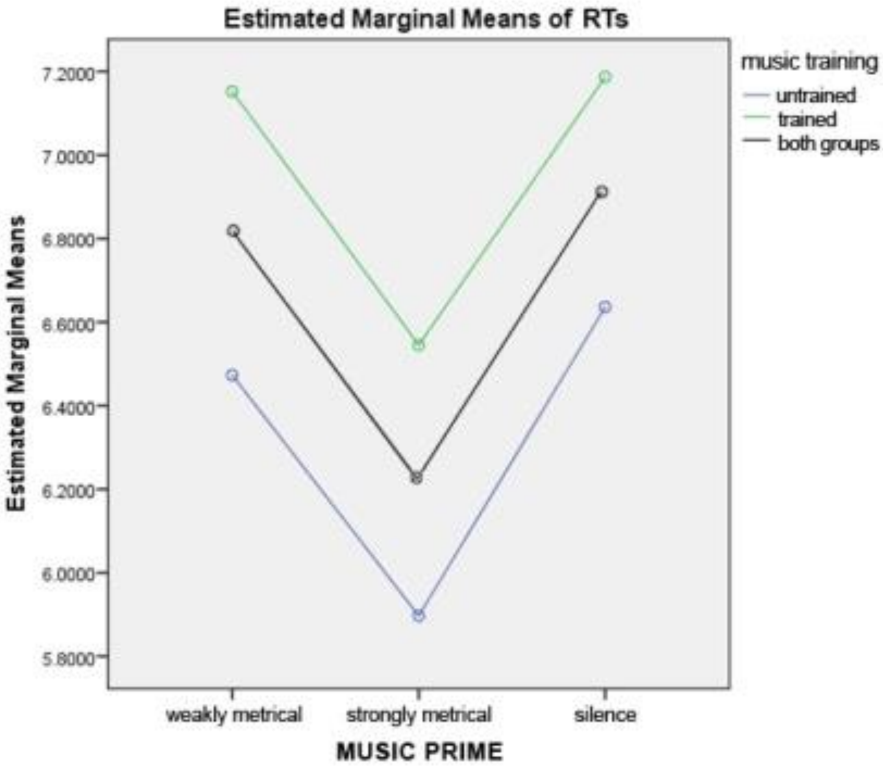

Figure 6. RTs plot averaged over participants, by musical prime (Strongly Metrical, Weakly Metrical, Silence) in the geometric sequences task.

In sum, in this experimental condition it was shown that both performance and reaction times of children with and without musical training can benefit from a strongly metrical prime in a grammatical but non-verbal and non-linguistic task in comparison with a weakly metrical prime and a baseline condition. Musically trained children were again shown to be more sensitive to rhythmical differences and thus more affected by them (positively by strongly metrical prime and negatively by weakly metrical prime). Response biases in this task were relatively small.

4.3 Shape Sets Task

For the *d'* (see Table 4) in the shape sets task, there was no interaction between musical prime and musicality, F (2, 48) = 0.64, p = .53, partial η^2 = .03. Both main effects of musical prime and musicality were also far from statistical significance, F (2, 48) = 0.44, p = .65, partial η^2 = .02 and F (1, 24) = 1.74, p = .20, partial η^2 = .07, respectively. No prime condition differed significantly from another regarding the performance of children with or without musical training, even though the first performed better than the latter after the weakly metrical prime, F (1, 24) = 2.06, p = .05, partial η^2 = .08.

The analysis of *c* (see Table 5) showed that the rhythmic priming effect found in the shape sets task performance was accompanied by slight differences in response bias. The main effect of musicality was statistically significant, F (1, 24) = 13.60, p = .001, partial η^2 = .36, the main effect of prime was close to marginally significant, F (2, 48) = 2.24, p = .12, partial η^2 = .09, but not their interaction, F (2, 48) = 0.52, p = .60, partial η^2 = .02. Children appeared to be slightly more liberal after hearing to silence compared to the metrically strong (MD= .24, p = .09) and the metrically weak prime (MD= .28, p = .08). Although children without musical education were again mildly conservative with almost no difference in their response bias between prime conditions, musically trained children appear to be significantly more liberal after hearing to silence compared to the weakly metrical prime, F (1, 24) = 1.77, p = .09, partial η^2 = .07. Moreover, children with music background appeared to be significantly more liberal than children without musical background in the strongly metrical prime condition, F (1, 24) = 3.05, p = .01, partial η^2 = .11, and in baseline condition, F (1, 24) = 2.53, p = .02, partial η^2 = .10. These findings should be accounted for the worse performance of musically trained children in silence condition and strongly metrical prime condition compared to the weakly metrical.

For the RTs (see Table 6) in the shape sets task, there was no interaction between musical prime and musicality, F (2, 48) = 0.72, p = .49, partial η^2 = .03. Both main effects of musical prime and musicality were also far from being statistically significant, F (2, 48) = 0.002, p = .99, partial η^2 < .01 and F (1, 24) = 0.06, p = .82, partial η^2 = .002, respectively. No prime condition differed significantly from another regarding the reaction times of children with or without musical training.

In sum, in the shape sets task both performance and RTs of children remained relatively unaffected of the different primes, independently of their music education.

We further performed supplementary ANOVAs for gender as additional between-participants factor, that was marginal in the linguistic task, F (1, 24) = 3.08, p = .09, partial η^2 = .11 and not significant in shape sequences, F (1, 24) = 0.40, p = .84, partial η^2 < .00 and sets, F (1, 24) = 0.82, p = .37, partial η^2 < .03.

5. General Discussion

The present study investigated whether musical primes can affect children's performance and reaction times in subsequent grammaticality judgement tasks of linguistic and non-linguistic content. Three types of primes were used, a strongly metrical, a weakly metrical, and a baseline of silence. Furthermore, children were separated in two groups, one with formal musical education for two consecutive years or more and one without any relevant training. In all tasks, children presented similar performance for silence independent from other factors, such as musicality, gender or socioeconomic status of parents. Thus, a baseline was successfully established and comparisons to different rhythmical primes could be safely drawn.

This experiment was successfully carried out for the first time in a language with not clear rhythmic classification. As discussed above, the rhythmic priming effect has already been observed in syllable stressed and syllable-timed languages (Chern et al., 2018; Ladanyi et al., 2020; Przybylski et al., 2013), but the fact that it is also present in Greek may suggest that the benefit of a strongly metrical rhythm may be a language general phenomenon. It should also be noted, that Greece, located on the eastern border of the western world has been receiving powerful musical influences of more complicated rhythmical patterns with less austere structure for thousands of years. This suggests that familiarity could be a less important factor of rhythmic prime than metricality.

As predicted, we found better performance in the linguistic task, replicating previous findings about better performance after a strongly compared to a weakly metrical prime (Chern et al., 2018; Przybylski et al., 2013) and to baseline (Bedoin et al., 2016). This finding is for the first time reported for a reading task involving whole sentences. We investigated the difference between the weakly structured prime to baseline, a comparison of great importance that controls for a possible detrimental effect of the weakly metrical prime. Ladanyi et al. (2020) initially expected to find a decline in performance after the prime with weak metricality as opposed to baseline, since Bedoin et al. (2016) observed a smaller size of the effect in their study (strongly metrical vs baseline) compared to that presented in Przybylski et al. (2013) (strongly metrical vs weakly metrical). Despite that, this particular contrast was shown to be non-significant in the study of Ladanyi et al. (2020), who inferred from this finding that a prime with weak metrical structure does not have a detrimental effect on a subsequent language processing task. Since rhythm is our factor, though, both non-metrical baseline conditions (environmental noise and silence) should bring similar effects as primes. We extended our research investigating the effect of musical training across all prime conditions and found that musically trained children were more influenced by the musical primes than the non-trained ones, probably as a result of their ability to discriminate between different metrical structures. Although a beneficial effect of the strongly metrical prime in contrast with silence was reported for both groups, musically trained children were shown to receive more from it and also suffer more from the weak metricality of the other rhythmic prime. This observation provides valuable information about the contrasts that have been reported so far, such as the fact that a child's rhythmical discrimination ability may determine the extent to which a strongly metrical prime could enhance the performance to a task or a poorly structured prime could deteriorate it. Except for playing musical instruments, a good understanding of rhythm can be achieved by a large number of activities that children are usually engaged in, such as dancing, singing, simply listening to music, etc. So, perhaps further investigating this factor could provide useful insights about the differences reported in the current literature between the actual effects of rhythmical primes.

These general findings were also reported in the sequence shape task. So far, children's performance was not improved by a strongly rhythmical prime in other visual tasks, such as target detection (Chern et al., 2018) and a non-verbal stroop task (Ladanyi et al., 2020). As we expected, we found better performance in the shape sequences task, a result that we attribute to its relevance to the matter of sequencing and temporal hierarchy that seems to be of great importance in priming effect research (Fitch & Martins, 2014).

The pattern between the three prime conditions was in fact more clear and definite in shape sequences than in the linguistic condition, as both performance and reaction times were much better after the strongly metrical prime than the weakly metrical prime and baseline. Several explanations could be given to this particular finding. Linguistic stimuli are much more complex to process, with greater load of information involving not only grammatical rules but also meaning. So, although we balanced the size of sentences with that of sequences (8 words – 8 shapes, respectively), children still had to make greater effort to process sentences.

This fact is vividly reflected on the mean difference of reaction times between the two tasks with all children responding generally faster (6,62s) in the shape sequences task than in the linguistic task (7,4s). It has to be noted that other researchers have used more trials per block (6 in Przybylski et al., 2013 and 10 in Landanyi et al., 2020), but their stimuli were auditorily presented, thus, children did not have to read the sentence nor the opportunity to go back and check before giving their answer. The latter also stopped every trial that lasted more than 5 seconds in order to use so big blocks without losing the effect of the prime, a practice that we avoided to exclude the stress factor. So, the faster reactions we reported in the less demanding shape sequence condition imply smaller duration of the whole block, which in turn involves greater influence of the prime and bigger size of the priming effect.

One other reason for the greater size of the observed priming effect in the shape sequences task compared to the linguistic task is the less diversity between the two groups. Musically trained and untrained children presented more converging data in the shape sequences task than in the linguistic task. The more plain and simple character of the rule under the shape sequences should also be accounted for this finding, since it helps to exclude other factors, such as meaning and semantic load.

Generally, we reported effects of small size as a result of several reasons. First, in order to exclude from our data factors other than the primes, such as ignorance or difficulty, we used easy-to-process trials and faced ceiling effect in all tasks. This effect was more intense because of the small number of trials per auditory condition (6 grammatical and 6 ungrammatical), and the slightly unbalanced relationship between grammatical and ungrammatical trials in some auditory conditions, initially allowed to avoid learning effects. The last factor was the moderate size of our sample, which, if increased, could have led our results to greater statistical significance.

In our last task we searched for a priming effect on a subsequent visual non-verbal task involving trials with shape sets, hierarchically organised in two dimensions of the spatial domain. Performance and reaction times of this task did not differ between the three primes across the two groups of children. This finding is aligned to the theoretical framework that distinguishes temporally and spatially hierarchical structures as subjected to the influence of musical primes or not, respectively (Fitch & Martins, 2014). According to this theory, shape sets do not involve temporal sequencing, as music, language and action, thus, they were not expected to be affected by rhythmical primes. This distinction is very important because it suggests that the rhythmic priming effect can extend to the visual domain, but only involving a process of sequential hierarchy such as grammar processing of multiple domains.

This finding could be proved extremely useful to understand the underlying mechanisms of rhythmic priming. The experimental design established here, provides an efficient method for evaluating the priming effect on visually presented stimuli of several fields. Thus, further experiments could be made, to test behavioural and physiological responses in visual tasks involving other domains with present temporal hierarchies. One good example could come from the field of mathematics, where certain operators (multiplication, division) have priority over others (addition, subtraction), despite being sequentially presented. Evidence for possible shared structural representations between language and mathematics come from recent research, in which the structure of a correctly solved mathematical equation influenced the relative-clause attachment in a subsequent sentence-completion trial (Scheepers et al., 2011). This suggests that the processing of temporally structured mathematical equations could also benefit from a strongly metrical prime, a fact with potentially far-reaching implications concerning the domain-generality of structural representation.

In a more practical level, metrical stimulation has been promoted as a therapeutic tool (Kotz et al., 2005), proven to be useful for several populations with impaired temporal processing, such as patients with Parkinson's disease (Kotz & Gunter, 2015) or lesions in the BG (Kotz, Gunter & Wonneberger, 2005). Moreover, children with developmental language disorders have been reported to present abnormalities in regions affecting one of the two pathways involved in sequencing and temporal attention described by Kotz & Schwarze (2010) and to benefit from a temporal stimulation with strong metrical structure (dyslexia: Goswami, 2011; Specific Language Impairment: Przybylski et al, 2013; and Developmental Language Disorder in general: Landanyi et al., 2020; for a review see Schon & Tillman, 2015). Our data include Greek children in the populations that can take advantage of music-based remediation and extend the cognitive fields that can receive these benefits to include other visually presented stimuli of temporal hierarchy, such as geometrical sequences. It is very important to include more cognitive tasks in this framework of cross-domain effects, in order to exploit the motivational advantages of music to provide a pleasant rehabilitation setting for more tasks.

6. Conclusion

Our study provides new evidence that rhythmic priming effect is present in Greek typically developed children, speaking a language without clear rhythmic classification, thus, suggesting that the benefit of a strongly metrical rhythm may be a language general phenomenon. Moreover, children were shown to be affected by rhythmic primes when reading whole sentences instead of hearing them auditorily. This experimental design allows direct comparisons between linguistic and visuo-spatial tasks, as it provides a general framework of visually presented stimuli.

Thus, it has been reported for the first time that the processing of a visuo-spatial task can also be enhanced by a strongly metrical rhythm, if temporal ordered hierarchies are involved. This finding extends the rhythmic priming effect to other cognitive fields suggesting its specificity to grammar processing in a domain-general sense. The implications of this result in cross-domain structural representation understanding and music-based rehabilitation are further discussed. Finally, the inclusion of a silence condition and the comparison between musically trained and untrained children reveal an important beneficial effect after a strongly metrical prime in contrast with silence and the weakly metrical one, but also a detrimental effect after the latter, especially for musically trained children. These data highlight the importance of musicality (and rhythm understanding) as a differentiating factor that has not been examined so far. Further research with bigger sample size and more trials per auditory condition could show more robust effects of rhythmic priming. Also, this effect should be tested on other cognitive tasks involving temporal ordered hierarchies, such as certain types of mathematical equations. Providing evidence for these cross-domain effects is encouraging and increases the possibilities of using rhythmic stimuli in remediating and training programs.

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