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How music training influences language processing: Evidence against informationnal encapsulation

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ABSTRACT

To investigate the modularity of language processing and, specifically, the question of whether the language module is informationally encapsulated, many experiments examined the impact of music expertise and music training on the language system (phonology, semantics and syntax). Finding positive evidence would argue against language as an independent ability isolated from other cognitive abilities. We first review the evolution of global or "massive" modularity, as advocated by Fodor in his influential book (1983), to reduced local modularity, (Fodor, 2003). We then consider experimental data relevant to these issues: the emerging picture favors the view that music abilities, as well as other cognitive abilities (attention, memory, executive functions) influence language processing. These influences are seen in behavior as well as in the complex brain networks that sustain behavior. In sum, evidence is accumulating supporting the idea that the language system is not independent from other cognitive abilities.

Keywords: Language, music, modularity

Comment l'entrainement musical influence le traitement du langage : Preuves contre l'encapsulation informationnelle

RÉSUMÉ

Afin de tester la modularité du traitement du langage et, plus spécifiquement, la question de savoir si le module du langage est informationnellement encapsulé, de nombreuses expériences ont eu pour but d'étudier l'influence de l'expertise musicale et de l'apprentissage de la musique sur le traitement linguistique, notamment aux niveaux phonologique, sémantique et syntaxique. Une influence positive démontrerait que le

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langage n'est pas une fonction isolée des autres fonctions cognitives. Nous considérons d'abord l'évolution d'une conception modulaire globale ou "massive", défendue par Fodor dans un livre paru en 1983 et qui a fortement influencé les recherches en sciences et neurosciences du langage, vers une conception plus locale et réduite de la modularité, comme revue par Fodor en 2003. Nous décrivons ensuite des données expérimentales qui montrent que les habiletés musicales, comme d'autres fonctions cognitives (attention, mémoire, fonctions exécutives), influencent le traitement du langage au niveau comportemental, aussi bien qu'au niveau des réseaux cérébraux complexes qui sous-tendent les comportements. Ainsi, de nombreux résultats sont en accord avec l'idée que le langage n'est pas indépendant des autres fonctions cognitives.
Mots-clés : Langage, musique, modularité

1. INTRODUCTION

Language, one of the most human ability[2], has long been considered as relying on specific, dedicated processes. However, in recent years, neurobiological models have emerged that emphasize the highly dynamic and distributed aspects of language processing. (Friederici & Singer, 2015; Hagoort, 2014; Hickok & Poeppel, 2007). Nevertheless, how these processes are implemented in the brain, how neuronal assemblies communicate together to allow us producing and comprehending language remains a major mystery. In the first section of this review, we consider the question of whether language is a domain-specific or domain-general cognitive ability in view of the evolution of the concept of modularity from massive modularity in Fodor (1983) to reduced local modularity in Fodor (2000/2003). Interestingly, the evolution of these philosophical considerations parallels progress in our understanding of the anatomo-functional organization of the brain developed in cognitive and computational neuroscience, from the old idea of one function-one structure (e.g., Gall, 1835 and the Classic ''Wernicke-Lichtheim-Geschwind" model) to many functions-one structure and many structures for one function (Park & Friston, 2013). In the second section, we focus on work considering the impact of music expertise and music training on language processing to test the following hypothesis: if language is a domain-specific and informationally-encapsulated ability, music expertise should have no influence on the various computations

[2] We consider that the language ability is subserved by different functions (categorical perception, speech segmentation etc…) and one aim is to determine whether (some of) these functions are also involved in music abilities.

involved in language processing. As we will see, many results in the literature allow us to reject this hypothesis.

2. MASSIVE MODULARITY VS LOCAL MODULARITY

In his book "The modularity of mind" (1983) that strongly influenced research in cognitive neuroscience for many years, Fodor defined a system as modular if it possesses a number of specific properties: (1) domain specific, (2) mandatory, (3) with limited access to the mental representations that they compute, (4) fast, (5) informationally encapsulated, (6) with 'shallow' outputs, (7) with characteristic and specific breakdown patterns, and (8) with a characteristic pace and sequencing of their ontogeny. In this framework[3], a module is a processing device that only uses the information available in its own innate database without being influenced by anything else (the extreme example of a modular system is a reflex). Importantly, Fodor clearly insisted that 'informational encapsulation is at the heart of modularity' (2003, p. 107) because this is how modules can be functionally specified. In this context, the "language organ" (Pinker, 1994) was typically considered as a modular system that included several hierarchically organized sub-modules dedicated to phonetic, phonologic, semantic, syntactic, pragmatic aspects of language processing, each sub-module doing its own computations without influence from other computational levels and transmitting the results of its own computations to the next hierarchical level.

Over the years, numerous results have accumulated against this view[4] that led Fodor to revise his conception of modularity in his less-known book, "The mind doesn't work this way" (2000/2003)[5], in which he considers that only local systems can be modular. Global systems are not modular

[3] The basic assumption underlying modularity, as defined by Fodor (1983), is that cognitive mental processes are computational (i.e. thinking is a form of computation). Cognitive processes are specific (logico-algebric) computations (i.e. formal — non-semantic- operations) on mental representations (i.e. the relationship between the world and the mind) that are structured syntactically (i.e. they obey an ensemble of rules that define the relationship between the different elements). However, this basic assumption has also been called into question by Fodor (2000).

[4] For instance, results typically highlighted strong interactions between different levels of language processing. To take only one example among many, Dehaene et al (2010) showed that learning to read increased the level of activation in brain regions involved in phonological processing (in the planum temporale) when listening to speech.

[5] Fodor (2000/2003) book was also possibly written in response to Pinker (1997) « How the mind works », W.W. Norton & Company, New York, London.

because they use all the information available within the entire system to compute their function (see also Hagoort, 2014). Applied to language, this implies that the language system is not informationally encapsulated because it does not work independently of other cognitive functions that provide relevant information (e.g., attention, memory…). Of course, the next problem is then to define local and global systems. Marr (1982) advocated the view that global systems can be decomposed into a collection of modular, independent, and specialized sub-processes[6]. In line with this view, Park & Friston (2013) more recently proposed a model that may possibly reconcile the modular and non-modular theoretical frameworks: "Brain functions can be characterized by local integration within segregated modules for specialized functions and global integration of modules for perception, cognition, and action". Thus, while micro neural circuits are possibly characterized by a modular architecture, macroscopic brain networks are non-modular and highly interactive, with a pattern of interactions that dynamically change over time as a function of context and task-demands ("functional integration among segregated brain areas" Friston, 2011). Importantly, Park & Friston (2013) proposed that at the level of the module (micro-neural circuits), functional connectivity (defined as "as statistical dependencies among remote neurophysiological events") is closely related to the underlying structural connectivity (defined as "the anatomical connections usually estimated using fiber tractography from diffusion tensor imaging, DTI"). Thus, at this level, there is possibly a one-function-to-one-structure mapping with the idea that structural networks are constraining functional networks. However, at the level of global systems such as language, there are many function-structure relationships so that a neuronal architecture can be involved in diverse cognitive functions and a global system such as language may rely on different brain structures.

Let's consider, for instance, Broca's area. It has long been considered that this region, in the left inferior frontal cortex (for the problems posed by its precise localization, see Tremblay & Dick, 2016), was specific to speech production and to processing of syntactic structures. However, there is now clear evidence that Broca's area is also activated by the processing of phonological, lexical and semantic information (Sahin, Pinker, Cash, Schomer, Halgren, 2009). Moreover, results also point to the activation of parts of Broca's areas in tasks requiring verbal and non-verbal working memory and/or executive functions (Schulze et al., 2011) as well as in

[6] It is important to note that this view was criticized as being open-ended with no empirical failure point: any processes can be decomposed into more refined sub-processes (Van Orden, Pennington, & Stone, 2001).

tasks based on the processing of musical syntax (Maess, Koelsch, Gunter & Friederici, 2001, see below). The same general picture also emerges when considering Wernicke's area (part of the Planum Temporale (PT) in the left Superior Temporal Gyrus (STG), with similar localization problems as for Broca's area; see Tremblay & Dick, 2016 and DeWitt & Rauschecker, 2013), that was initially taken to play a major role in language comprehension. Temporal regions are clearly crucial for speech processing but there is also growing evidence for their functional diversity, with sub-areas implied both in linguistic and in nonlinguistic functions (see Liebenthal, Desai, Humphries, Sabri, & Desai, 2014 for results of a large meta-analysis). Taken together, these results are important for at least two reasons. First, they strongly call into question the one structure-one function mapping between Broca's or Wernicke'areas and speech production, syntax processing and speech comprehension. Broca's or Wernicke's area do not appear to be the brain structures hosting a speech production module, a syntactic module or a speech comprehension module that would carry on its own computations autonomously, without being influenced by other levels of language processing or by other cognitive functions. Although the localization and functional role of Broca's and Wernicke's areas are still under debate (Tremblay & Dick, 2016), current evidence suggests that they may be part of a large prefrontal-temporal network, that includes language-specific as well as general cognitive functions that closely interact with one another (Fedorenko, Duncan, & Kanwisher, 2012; Hagoort, 2014; Schulze et al., 2011).

Second, the repeated finding that Broca's area is not only involved in syntactic processing but also in phonological, lexical and semantic processing more generally argues against the idea that syntactic constructions are processed independently from lexico-semantic information, or put the other way around, these findings argue in favor of the idea that syntactic constructions have meaning. Showing that Broca area is activated by syntactic as well as by lexico-semantic processing is indeed compatible with linguistic theories issued from Cognitive and Construction Grammar (e.g., Goldberg, 1995, Langacker, 1991) that consider that there is no clear separation between syntax and lexico-semantic information. As clearly stated by Goldberg (1995, p.7): "In Construction Grammar, no strict division is assumed between the lexicon and syntax. Lexical constructions and syntactic constructions differ in internal complexity, […] but both lexical and syntactic constructions are essentially the same type of declaratively represented data structure: both pair form with meaning." For instance, two apparently similar grammatical constructions may induce differences in meaning: in "*Bill* *sent a walrus to Joyce*" the accent is on the salience of the path due to the use of "to" but in "*Bill sent Joyce a walrus*", the accent is on the salience of the possessive relationship due to the use of a ditransitive construction. Another example: "*Sally baked her sister a cake*", Sally baked a cake with the intention to give it to her sister and this intention is inferred from the grammatical construction (not present in the verb "to bake")[7]. Within this framework, we previously showed that the same syntactic incongruity (an intransitive verb followed by a direct object) was processed differently depending upon the semantic context of the sentence. Thus, while there was no significant differences between the correct sentence (.g., "L'ennemi a préparé un complot", 'The enemy prepared a scheme') and the syntactically incongruous sentence with congruent semantics (e.g., *L'ennemi a conspiré (INTR) un complot, 'The enemy conspired a scheme'), the differences observed in behavior (percent errors) and in electrophysiological measures (N400 and P600 components) were significant when the semantics of the sentence did not help resolve the syntactic incongruity (e.g., *L'ennemi a déjeuné (INTR) un complot", *'The enemy lunched a scheme' (Magne, Besson & Robert, 2014). To end this short and incomplete section on the relationships between syntax and semantics, we refer the interested reader to the book by Tomasello (1998) "The new psychology of language" in which Langacker position is clearly summarized: "The ultimate goal is not to create a mathematically coherent grammar that normatively parses the linguistic universe into grammatical and ungrammatical sentences but rather to detail the structured inventory of symbolic units that make up particular natural languages" (p.xiii).

3. HOW MUSIC EXPERTISE AND MUSIC TRAINING INFLUENCE LANGUAGE PROCESSING

To further test whether language is a domain-specific and informationally-encapsulated ability, we now focus on the specific issue of the influence of music expertise and music training[8] on the various computations involved in language processing. The central hypothesis is

[7] We are thankful to Dr Stéphane Robert for providing us with these examples.

[8] Music expertise refers to musicians that are already experts in the domain (i.e., professional musicians). By contrast, music training refers to participants that are currently being trained in music and who are not yet musicians.

that if the language system is an informationnaly encapsulated module, it should be impermeable to the influence of other cognitive abilities. Consequently, if we can demonstrate that musical abilities, as well as other cognitive abilities (attention, memory, executive functions, not reviewed here) impact language processing (categorical perception, segmental and supra-segmental processes, phonology, syntax and semantics), these findings would argue against one of the main characteristics of a modular system: encapsulation. Below we review evidence showing that these influences can be seen in behavior as well as in the complex brain networks that sustain behavior.

Categorical perception is fundamental to speech perception by allowing listeners to categorize continuous acoustic changes in the speech signal into discrete phonetic categories. Bidelman and collaborators (2014) first demonstrated that music training in both younger and older musicians is associated with more efficient vowel categorical perception (/u/ to /a/ continuum) as reflected by behavioral measures, more precise phase-locking of brainstem responses and increased amplitude of cortical evoked responses to relevant speech cues. Moreover, Habib and collaborators (2016) tested the efficacy of a newly developed cognitivo-music training method to improve categorical perception in children with dyslexia. They showed a normalization of the identification and discrimination of inter-categorical boundary on a /ba/-/pa/ continuum after intensive music training clustered on three consecutive days as well as after distributed music training over a 6 weeks period. Thus, increased auditory sensitivity in musicians and in children with music training is possibly one of the driving forces behind enhanced categorical perception in musicians.

Speech segmentation is also fundamental to speech comprehension as is clearly exemplified when learning a foreign language that is first perceived as a continuous stream of nonsense words. François and colleagues (2013) used a longitudinal approach over two school-years with 8 years old children to examine the impact of music compared to painting training on the ability to extract "words" from a continuous stream of meaningless sung syllables. Implicit recognition of meaningless words steadily increased over the two years of music but not of painting training and this was associated with modulations of a frontally distributed N400 component (FN400).

At the segmental level (consonants, vowels and syllables), music training is correlated to the discrimination of Mandarin tones in native English-speakers (Lee & Hung, 2008) and of lexical tones in Italian speakers (Delogu, Lampis & Belardinelli, 2010). Moreover, Marie, Delogu, Lampis, Belardinelli & Besson (2011) showed that, at the cortical level, both lexical tone discrimination (as reflected by the N200/N300 component) and higher-order decision processes (as reflected by the P300b component) were more efficient in musicians than in non-musicians. Very recently, Dittinger et al (2018) tested the impact of musical expertise on the categorization of syllables that did (/p/, /b/) or did not (/ph/) belong to the French repertoire. Professional musicians outperformed non-musicians when the task required the discrimination of non-native phonemes, and the difference between native and non-native phonemes, as reflected by the N200 and P300 components, was larger in musicians than in non-musicians. Finally, in the study mentioned above, Habib et al (2016) also showed that music training improved the perception of syllabic duration in children with dyslexia.

At the supra-segmental level (words, sentences, discourse), early research showed that adult musicians and children with music training are more sensitive than non-musicians to linguistic prosody (e.g., final pitch rise in sentences; see Besson and coll. 2011, for review) and to emotional prosody (Lima & Castro, 2011; but see Trimmer & Cuddy, 2008, for contrastive results). Follow-up studies by Moreno and coll. (2009) used a longitudinal approach to compare non-musician children (8-12 years old) before and after 6 months of music or painting training. Results showed enhanced perception of prosodic intonation only in the music group, together with better reading abilities of complex words.

At the phonological level, there is evidence that musical abilities are predictive of phonological skills in children (Anvari, Trainor, Woodside & Levy, 2002) and in adults (Slevc & Miyake, 2006). These results, based on a cross-sectional approach, are in line with those of a longitudinal study with 6-7 years old children showing that two months of rhythm-based training produced roughly comparable enhancements on a variety of standardized tests of phonological processing than an equivalent amount of training of phonological skills (Bhide, Power & Goswami, 2013). They are also in line with the conclusions of an interesting meta-analysis of longitudinal studies conducted by Gordon, Fehd & McCandliss (2015) showing that music training significantly improved phonological awareness skills, even if the effect sizes were small. By contrast, these analyses also revealed that the evidence for an impact of music training on reading had not yet been convincingly demonstrated.

At the syntactic level, Jentschke & Koelsch (2009) reported that, as expected, violations of harmonic structures elicited larger cortical responses in musically trained children than in controls. More surprisingly, violations of linguistic structures also elicited the largest effects in musically trained children, which was taken as evidence that the automatic processing of linguistic syntactic structures developed faster in children with than without music training, possibly because syntax relies on similar processes in both music and language or because musically-trained children made better use of the prosodic and rhythmic cues that constrain syntactic constructions (Cason & Schön, 2012). Results by Gordon et al (2014) also support this interpretation: children with stronger rhythmic abilities also showed higher grammatical competence, as measured by their ability to produce sentences with relevant grammatical constructions. Taken together, these results are in line with early findings using fMRI and showing that Broca's area is activated when processing music as well as linguistic syntax (Maess et al, 2001), that is, when processing structured sequences of events that unfold in time, independently of whether these events form linguistic sentences or musical phrases.

Finally, at the semantic level, Dittinger and collaborators, recently provided evidence that novel word learning was faster and more efficient in professional musicians (Dittinger et al, 2016), in children with music training (Dittinger et al, 2017) and, although the differences were smaller, in older musicians (Dittinger et al, submitted.) than in controls. Specifically, participants were first asked to learn the meaning of monosyllabic Thaï words through picture-word associations (see Figure 1). A frontal N400 component (FN400), taken as an index that words had acquired meaning (Mestres-Misse, Rodriguez-Fornells & Münte, 2007), developed after only 3 minutes of training which clearly reflected fast brain plasticity. Importantly, the N400 developed faster in musicians than in non-musicians (see Figure 2). To test whether participants had learned the associations, a matching task was used in which picture-word pairs were presented that matched or mismatched those learned in the learning phase. Finally, to test for semantic generalization, new pictures (not seen before in the experiment) were presented that were semantically related or unrelated to the newly-learned words (see Figure 1). In both the matching and semantic tasks, the N400 effect (i.e., the difference between mismatching/unrelated and matching/related words) was larger in musicians than in non-musicians (see Figure 3). As typically found in the literature, the N400 effect was larger over centro-parietal regions in musicians but it was more frontally distributed in non-musicians. This was taken as evidence that musicians were more efficient at integrating the meaning of novel words into semantic networks than non-musicians and this was in line with their higher level of performance in the semantic task.

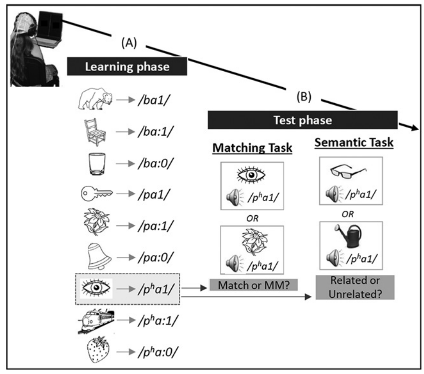

Figure 1. Schematic representation of the experimental procedure that included a learning phase and a test phase (see text for details).

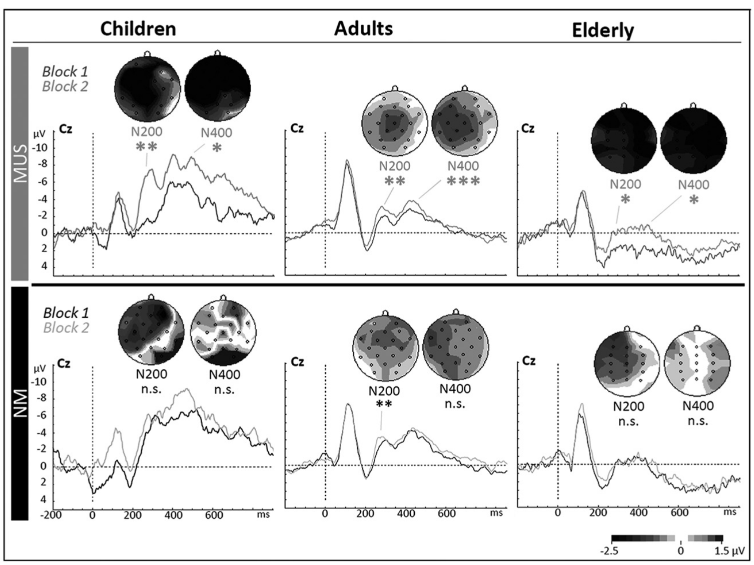

Figure 2. Event-Related Potentials (ERPs) recorded in the learning phase, when children with music training, professional young musicians and elderly musicians (top row) and non-musician controls (bottom row) learned the meaning of novel words through picture-word associations. ERPs recorded at the central site (Cz) to the words are compared between the first and the second learning blocks and the differences are significant for the N200 and N400 components in musicians but not in non-musicians. Topographical maps are presented to illustrate the differences in scalp distribution of these components between Block 1 and Block 2 of the learning phase. On this figure and on the next one, time is on the abscissa (in milliseconds, ms) and the amplitude of the effects is on the ordinate (in microvolts, µV).

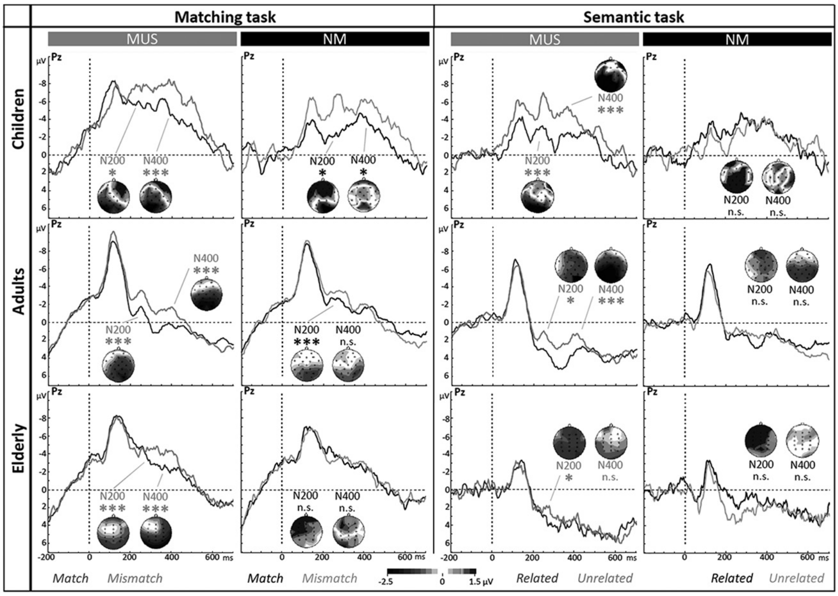

Figure 3. ERPs recorded in the test phase, when children with and with no music training (top row), professional young-adult musicians and non-musician adults (middle row) as well as elderly musicians and elderly controls (bottom row) and non-musician controls (bottom row) performed the matching task (left columns) and the semantic task (right columns). ERPs recorded at the parietal site (Pz) are compared between words that matched or mismatched the picture association learned previously in the matching tasks as well as between words that were semantically related or unrelated to new pictures. In both tasks and in the three groups of participants, effects on the N200 and N400 components were overall significantly larger in musicians than in controls. Topographical maps are presented to illustrate the scalp distribution of the effects.

How can we account for these effects and more generally for the influence of music training at various levels of language processing? Two main interpretations, the cascade and multi-dimensional interpretations, have been proposed. Following the cascade interpretation (bottom-up), increased sensitivity to low-level acoustic parameters such as pitch or duration, that are common to music and speech, drives the influence of music training at different levels of language processing (e.g., phonetic, phonologic, prosodic, syntactic and semantic; Wong, Skoe, Russo, Dees, & Kraus, 2007; Besson et al, 2011; Dittinger et al, 2016). In other words, because musicians perceive speech sounds better than non-musicians, they are more sensitive to prosodic cues such as pitch and rhythm and they form more accurate phonological representations. This, in turn (hence the cascade), increases the stability of lexical representations and facilitates the construction of syntactic structures, word learning and semantic processing.

Following the multi-dimensional interpretation (top-down), that shares several aspects with the OPERA hypothesis proposed by Patel (2014), both language and music are processed in interaction with other cognitive, emotional and motor abilities. For instance, playing a music instrument is a multi-dimensional ability that requires auditory and visual perception (auditory processing of sounds and visual processing of notes on the score), auditory-visuo-motor integration (playing and hearing the notes visually presented on the score), selective and divided attention (focusing attention on one's own instrument and dividing attention between the different instruments of the orchestra and the conductor…), motor control (posture and fine movements of the hands, elbow, lips…), memory (playing musical pieces by heart is common practice in professional musicians), cognitive control (executive functions, such as cognitive flexibility, inhibitory control and working memory, see Zuk, Benjamin, Kenyon & Gaab, 2014) and emotion (as reflected by the interpretation of the musical piece). Thus, it may come as no surprise that extensive training of these different abilities in musicians, from auditory perception to cognitive control, facilitates various levels of language processing. In this respect the cascade and multi-dimensional hypotheses are complementary with both bottom-up and top-down processes probably at play to various degrees in most experimental designs. Results of speech in noise perception experiments also support this view, by showing that the fidelity of the brainstem response is correlated with the ability to hear speech in noise that, in turn, is correlated with auditory working memory, thereby pointing to both bottom-up and top-down influences between the subcortical and cortical levels of speech processing (e.g., Kraus, Strait & Parbery-Clark, 2012).

Directly related to the issue raised in this second section, the results reviewed above clearly demonstrate that the various language processing levels that have been examined so far (categorical perception, speech segmentation, phonology, syntax and semantics) are not impermeable to the influence of music expertise and music training. It is therefore unlikely that language functions as an informationally encapsulated module, independently from other cognitive abilities.

4. CONCLUSION

Science is a never-ending process and more experiments are clearly needed to better understand the influence of music expertise and music training on language processing at the behavioral level, by testing groups of participants with wide range of musical abilities, by using standardized tests when they are available and by trying to control for the effects of the many different factors that can influence the results (the task at hand, socio-economic status, bilingualism…) using different statistical analyses based, for instance, on structural equation modelling. At the brain level, approaches based on structural and functional connectivity and, may be more importantly, on effective connectivity as derived from computational modelling, are very promising avenues for future research.

Another issue that we did not address here is whether the many associations between music expertise and the various levels of language processing reviewed above are causally linked to music training. Indeed, some authors have argued that children with good music aptitudes (Swaminatha & Schellenberg, 2017) or with higher intelligence (IQ, Schellenberg, 2011) are more likely to take music lessons than children with lower music aptitudes or IQ scores. While this may be the case, results of longitudinal studies have also shown that music training can causally influence language processing. For instance, non-musician children trained with music for six or 12 months showed improved pre-attentive processing of segmental cues (vowel duration and voice-onset-time; Chobert et al, 2014) as well as increased perception of prosodic cues and better reading of complex words (Moreno et al., 2009) compared to children trained with painting. Taken together, these results and others suggest that both nature and nurture contribute to the strong influence of music training on language processing.

Based on the above, we would like to point out what we consider as two major advances in the sciences of language. First, as a global system, language can no longer be considered as an autonomous "mental organ" (Pinker, 1994) relying on specific, dedicated processes (Fodor, 1983**). Rather, current evidence favors the view that language comprehension and production are processed in interaction with other cognitive abilities such as attention, memory, emotions and actions (Fodor, 2000).** As nicely written in the article by Tremblay & Dick (2016) that motivated this special issue: "As a field, we need to study the interactions between language and other functional systems in order to fully understand the neurobiological underpinning of human language and language disorders, and the degree to which it is dependent upon various other cognitive, sensorimotor and emotional processes, all of which must come together to put language into action."

Second, while we are still far from understanding the mind-brain relationship and how neuronal assemblies can produce thoughts, language and music…, advances in brain imaging methods allow us to go beyond the localizationist idea of one-to-one mapping between structures and functions (Gall, 1835; Broca, 1863) to address the much more complex, but probably more realistic view of many functions for one structure and many structures for one function (Park & Friston, 2013). This is also reflected in the evolution of the neurobiological models of language, from static boxes connected with stable arrows to dynamic brain networks, *à la Facebook*, with the strength of connections, nodes and hubs strongly and rapidly fluctuating over time to consider all available information at particular moment in time (Friederici & Singer, 2015; Hagoort, 2014; Hickok & Poeppel, 2007). The convergence in the evolution of philosophical, linguistics and cognitive neuroscience approaches makes us very optimist that a "true" interdisciplinarity is born that will go beyond the old debates to open new perspectives on the complex mind/brain problem.

REFERENCES

Anvari, S. H., Trainor, L. J., Woodside, J., & Levy, B. A. (2002). Relations among musical skills, phonological processing, and early reading ability in preschool children. *Journal of experimental child psychology*, *83*(2), 111-130.

Besson, M., Chobert, J., & Marie, C. (2011). Transfer of training between music and speech: common processing, attention, and memory. *Frontiers in psychology*, *2*, 94.

Bhide, A., Power, A., & Goswami, U. (2013). A rhythmic musical intervention for poor readers: A comparison of efficacy with a letter-based intervention. *Mind, Brain, and Education*, *7*(2), 113-123.

Bidelman, G. M., Weiss, M. W., Moreno, S., & Alain, C. (2014). Coordinated plasticity in brainstem and auditory cortex contributes to enhanced categorical speech perception in musicians. *European Journal of Neuroscience*, *40*(4), 2662-2673.

Broca, P. (1863). *Localisations des fonctions cérébrales. Siège de la faculté du langage articulé.* Bulletin de la Société d»Anthropologie 4: 200–208.

Cason, N., & Schön, D. (2012). Rhythmic priming enhances the phonological processing of speech. *Neuropsychologia*, *50*(11), 2652-2658.

Delogu, F., Lampis, G., & Belardinelli, M. O. (2010). From melody to lexical tone: Musical ability enhances specific aspects of foreign language perception. *European Journal of Cognitive Psychology*, *22*(1), 46-61.

DeWitt, I., & Rauschecker, J. P. (2013). Wernicke's area revisited: parallel streams and word processing. *Brain and language*, *127*(2), 181-191.

Dittinger E, Valizadeh SA, Jäncke L, Besson M, Elmer S. (submitted). Testing Relationships between Music Training and Word Learning across the Lifespan by using Cross-Sectional and Comparative Electrophysiological Approaches in Children, Adults, and Elderlies. *NeuroImage*.

Dittinger, E., Barbaroux, M., D'Imperio, M., Jäncke, L., Elmer, S., & Besson, M. (2016). Professional music training and novel word learning: from faster semantic encoding to longer-lasting word representations. *Journal of cognitive neuroscience*, *28*(10), 1584-1602.

Dittinger, E., Chobert, J., Ziegler, J. C., & Besson, M. (2017). Fast brain plasticity during word learning in musically-trained children. *Frontiers in human neuroscience*, *11*, 233.

Dittinger, E., D'império M. & Besson, M. (2018). Enhanced neural and behavioral processing of a non-native phonemic contrast in professional musicians. *European Journal of Neuroscience, 1-13.*

Fedorenko, E., Duncan, J., & Kanwisher, N. (2012). Language-selective and domain-general regions lie side by side within Broca's area. *Current Biology*, *22*(21), 2059-2062.

Fodor, J. (2000/2003). *The mind doesn't work this way*. Cambridge MA: MIT Press.

Fodor, J. A. (1983). *The modularity of mind*. Cambridge MA: MIT Press.

François, C., Chobert, J., Besson, M., & Schön, D. (2013). Music training for the development of speech segmentation. *Cerebral Cortex*, *23*(9), 2038-2043.

Friederici, A. D., & Singer, W. (2015). Grounding language processing on basic neurophysiological principles. *Trends in Cognitive Sciences*, *19* (6), 329–338.

Friston, K. J. (2011). Functional and effective connectivity: a review. *Brain connectivity*, *1*(1), 13-36.

Gall, F. J. (1835). *On the functions of the brain and of each of its parts: With observations on the possibility of determining the instincts, propensities, and talents, or the moral and intellectual dispositions of men and animals, by the configuration of the brain and head (Vol. 1).* Marsh, Capen & Lyon.

Goldberg, A. E. (1995). *Constructions: A construction grammar approach to argument structure*. University of Chicago Press.

Gordon, R. L., Fehd, H. M., & McCandliss, B. D. (2015). Does music training enhance literacy skills? A meta-analysis. *Frontiers in psychology*, *6*, 1777.

Gordon, R. L., Shivers, C. M., Wieland, E. A., Kotz, S. A., Yoder, P. J., & Devin McAuley, J. (2014). Musical rhythm discrimination explains individual differences in grammar skills in children. *Developmental Science*, *18*(4), 635-644.

Habib, M., Lardy, C., Desiles, T., Commeiras, C., Chobert, J., & Besson, M. (2016). Music and dyslexia: a new musical training method to improve reading and related disorders. *Frontiers in psychology*, *7*, 26.

Hagoort, P. (2014). Nodes and networks in the neural architecture for language: Broca's region and beyond. *Current Opinion in Neurobiology*, *28*, 136–141.

Hickok, G. & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience, 8*, 393-402.

Jentschke, S., & Koelsch, S. (2009). Musical training modulates the development of syntax processing in children. *Neuroimage*, *47*(2), 735-744.

Kraus, N., Strait, D. L., & Parbery-Clark, A. (2012). Cognitive factors shape brain networks for auditory skills: spotlight on auditory working memory. *Annals of the New York Academy of Sciences*, *1252*(1), 100-107.

Langacker, R. W. (1991). Cognitive grammar, in *Linguistic theory and grammatical description*. F. Droste and J. Joseph (eds), 275-306. Amsterdam: John Benjamins.

Lee, C. Y., & Hung, T. H. (2008). Identification of Mandarin tones by English-speaking musicians and nonmusicians. *The Journal of the Acoustical Society of America*, *124*(5), 3235-3248.

Liebenthal, E., Desai, R. H., Humphries, C., Sabri, M., & Desai, A. (2014). The functional organization of the left STS: a large scale meta-analysis of PET and fMRI studies of healthy adults. *Frontiers in neuroscience*, *8*, 289.

Lima, C. F., & Castro, S. L. (2011). Speaking to the trained ear: musical expertise enhances the recognition of emotions in speech prosody. *Emotion*, *11*(5), 1021.

Maess, B., Koelsch, S., Gunter, T. C., & Friederici, A. D. (2001). Musical syntax is processed in Broca's area: an MEG study. *Nature neuroscience*, *4*(5), 540-545.

Magne, C., Besson, M., & Robert, S. (2014). Context influences the processing of verb transitivity in French sentences: more evidence for semantic– syntax interactions. *Language and Cognition*, *6*(2), 181-216.

Marie, C., Delogu, F., Lampis, G., Belardinelli, M. O., & Besson, M. (2011). Influence of musical expertise on segmental and tonal processing in Mandarin Chinese. *Journal of Cognitive Neuroscience*, *23*(10), 2701-2715.

Marr, D. (1982). *Vision*. San Fransico, CA: Freeman.

Mestres-Missé, A., Rodriguez-Fornells, A., & Münte, T. F. (2006). Watching the brain during meaning acquisition. *Cerebral Cortex*, *17*(8), 1858-1866.

Moreno, S., Marques, C., Santos, A., Santos, M., Castro, S. L., & Besson, M. (2008). Musical training influences linguistic abilities in 8-year-old children: more evidence for brain plasticity. *Cerebral Cortex*, *19*(3), 712-723.

Park, H. J. & Friston, K. (2013). Structural and functional brain networks: from connections to cognition. *Science, 342*, 579-588

Patel, A. D. (2014). Can nonlinguistic musical training change the way the brain processes speech? The expanded OPERA hypothesis. *Hearing research*, *308*, 98-108.

Pinker, S. (1994). *The language instinct*. Harper Perennial Ed., 1995.

Sahin, N. T., Pinker, S., Cash, S. S., Schomer, D., & Halgren, E. (2009). Sequential processing of lexical, grammatical, and phonological information within Broca's area. *Science*, *326*(5951), 445-449.

Schulze, K., Zysset, S., Mueller, K., Friederici, A. D., & Koelsch, S. (2011). Neuro-architecture of verbal and tonal working memory in nonmusicians and musicians. Human brain mapping, 32(5), 771-783.

Slevc, L. R., & Miyake, A. (2006). Individual differences in second-language proficiency: Does musical ability matter? *Psychological Science*, *17*(8), 675-681.

Tomasello, M. (1998). *The new psychology of language*. London: Erlbaum.

Tremblay, P., & Dick, A. S. (2016). Broca and Wernicke are dead or moving past the classic model of language neurobiology. *Brain and language*, *162*, 60-71.

Trimmer, C. G., & Cuddy, L. L. (2008). Emotional intelligence, not music training, predicts recognition of emotional speech prosody. *Emotion*, *8*(6), 838.

Wong, P. C., Skoe, E., Russo, N. M., Dees, T., & Kraus, N. (2007). Musical experience shapes human brainstem encoding of linguistic pitch patterns. *Nature neuroscience*, *10*(4), 420.

Zuk, J., Benjamin, C., Kenyon, A., & Gaab, N. (2014). Behavioral and neural correlates of executive functioning in musicians and non-musicians. *PloS one*, *9*(6), e99868.

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