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Electrophysiological evidence for a specific neural correlate of musical violation expectation in primary-school children

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ABSTRACT

The majority of studies on music processing in children used simple musical stimuli. Here, primary schoolchildren judged the appropriateness of musical closure in expressive polyphone music, while high-density electroencephalography was recorded. Refined in-key harmonic transgressions at closure were presented interspersed with regular endings. The children discriminated the transgressions well above chance. Regular and transgressed endings evoked opposite scalp voltage configurations peaking around 400 ms after stimulus onset with bilateral frontal negativity for regular and centro-posterior negativity (CPN) for transgressed endings. A positive correlation could be established between strength of the CPN response and rater sensitivity (d-prime). We also investigated whether the capacity to discriminate the transgressions was supported by auditory domain specific or general cognitive mechanisms, and found that working memory capacity predicted transgression discrimination. Latency and distribution of the CPN are reminiscent of the N400, typically observed in response to semantic incongruities in language. Therefore our observation is intriguing, as the CPN occurred here within an intra-musical context, without any symbols referring to the external world. Moreover, the harmonic in-key transgressions that we implemented may be considered syntactical as they transgress structural rules. Such structural incongruities in music are typically followed by an early right anterior negativity (ERAN) and an N5, but not so here. Putative contributive sources of the CPN were localized in left pre-motor, mid-posterior cingulate and superior parietal regions of the brain that can be linked to integration processing. These results suggest that, at least in children, processing of syntax and meaning may coincide in complex intra-musical contexts.

Introduction

Western tonal music relies on a rule system of hierarchical pitch relationships around a key "center" or tonic. In order to study tonal expectation violation, unexpected pitches that transgress this rule system are embedded in musical contexts. This has been done either in monophonic material, tone sequences or melodies (Besson and Faïta, 1995; Nittono et al., 2000; Trainor and Trehub, 1994), or in harmonic progressions, the latter either in chord sequences (Bigand et al., 2003; Koelsch et al., 2001, 2007; Regnault et al., 2001) or in complex polyphone music (James et al., 2008; Koelsch et al., 2008; Koelsch and Mulder, 2002; Oechslin et al., 2013b; Steinbeis et al., 2006). If these transgressions are in-key or in a closely related key, they are generally considered syntactical, because they transgress mainly structural or grammatical rules (James et al., 2008; Koelsch, 2011; Koelsch et al., 2007; Patel, 2003; Tillmann et al., 2006). Such is the case of the stimuli we used in the present investigation.

Brain substrates processing musical tonal expectation violation have been shown to overlap, neighbor or mirror in the contralateral (right) hemisphere those for syntax processing in language in the left hemisphere (Friederici, 2002), in particular in the inferior frontal cortex (Brown et al., 2006; Maess et al., 2001; Oechslin et al., 2013b; Tillmann et al., 2006). A plausible observation, as both language and music articulate discrete elements in embedded hierarchical structures of increasing complexity (James, 2012; Schon and Francois, 2011). Like in language, not only local but also long-distance structural dependencies are essential for syntactic processing in musical contexts, for instance regarding musical closure at the end of a phrase (James et al., 2008; Koelsch et al., 2013; Steinbeis et al., 2006).

That music also may convey meaning is widely accepted (Koelsch, 2011; Koelsch et al., 2004; Meyer, 1956; Swain, 1997), however, the nature of meaning in intra-musical contexts is intrinsically different

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from that in language, not concrete and varying between individuals even of the same culture (Lamont and Webb, 2010). Intra-musical meaning emerges as a function of interaction between musical formal structures, without any reference to the external world by means of words or other symbols (Koelsch, 2011).

In the context of pitch processing, a melody in major versus minor mode, or a deceptive versus a perfect cadence, convey different meanings; although hard to verbalize, then: music may express the ineffable (Jankélévitch and Abbate, 2003). Some evidence exists that cognitive mechanisms for higher order pitch processing, important for conveying semantic meaning in language, may be shared between language and music (Perrachione et al., 2013). Despite all these observations, some authors in the linguistic domain strongly deny any existence of semantics in music (Kutas and Federmeier, 2011; Pinker, 1997).

The N400 response is an event-related potential (ERP) presumed to process meaning. Initially observed in response to semantically incongruent sentence endings in language (Kutas and Hillyard, 1980), the N400 was more recently linked to incongruity of meaning in a wide variety of stimuli (Kutas and Federmeier, 2011). However, Kutas and Federmeier (2011) explicitly exclude musical stimuli from this train of results, suggesting that music does not contain semantically meaningful information.

Nevertheless Koelsch et al. (2004) could demonstrate a semantic priming effect on target word processing by means of musical primes and therefore provided evidence in favor of semantic processing in music. Primes consisted of sentences or musical passages that were either related or unrelated to a target word for their meaning. Independently of whether a musical or a language prime was used, unexpected target words provoked stronger N400 responses than target words preceded by related primes. The priming effect did not differ between language and musical primes for strength, time course or neuronal generators. This N400 response primed by musical targets was elicited by words and not by music; such a response to unexpected "extra-musical meaning" results from an association from a musical sign quality to the extra-musical world (Koelsch, 2012). Daltrozzo and Schon studied the reverse effect: the influence of visually presented words on the processing of musical excerpts (Daltrozzo and Schon, 2009). They also found a larger N400 response now in response to musical targets that were unrelated to the preceding extra-musical word context. These studies investigated people with low level of musical education or none.

In intra-musical contexts, transgression of intra-musical meaning by means of harmony transgression (thus violation of syntax) embedded in either chord series (Koelsch et al., 2000) or authentic musical stimuli (Koelsch et al., 2008), yielded an N5 response in non-musicians preceded by an ERAN (Koelsch et al., 2001).

Children and adults with and without formal musical education are able to discriminate tonal transgressions in melodies, chord progressions and complex music (Besson and Faïta, 1995; Bigand et al., 2003; Koelsch et al., 2000, 2005; Trainor and Trehub, 1994). Recently we could show that primary-school children with and without musical training perfectly rank transgressions of musical closure as a function of their salience in monophonic children's songs but also in more complex polyphone piano pieces (James et al., 2012). Moreover, typical ERP responses, similar to those of adults, occurred in 5- and 9-year old non-musician children in response to unattended chord series with transgressed endings (Koelsch et al., 2003). Whether these behavioral and associated ERP responses persist in primary-school children when irregularities are in-key and refined, moreover embedded in complex polyphone music, has not been investigated yet.

In the current experiment we presented a series of ecologically valid short string quartets (duration approx. 10 s) in a variety of Western tonal styles, to 15 randomly assigned primary-school children of around ten years of age. The pieces ended either regularly or contained refined in-key harmonic transgressions at closure. Notably, the transgressed and thus unexpected terminal chords were perceptually just as pleasant as the regular endings (see the Methods section, musical violation discrimination task). Meanwhile high-density electroencephalography (EEG) was recorded, that we analyzed with microstate analyses comprising all electrodes, and also with classical ERP analyses, using an electrode array deriving from a previous study (James et al., 2008).

As similar stimuli have not been presented to a child population before, our study is essentially exploratory, and cannot be placed in a full developmental context. However, we anticipated possible occurrence of early and later ERP components known to arise in response to tonal expectation violation in music in adults and children. In order to investigate whether the processing of structure and meaning in music is related to certain domain general cognitive functions, we additionally assessed measures of working memory and fluid intelligence.

Methods

Participants

Sixteen right-handed children (8 girls, 7 boys; mean age = 10.9 years, SD = 0.8) were randomly assigned among the population of a local public primary school. Their parents gave written informed consent. One child was excluded from the sample because of excessive blinking during EEG recordings. The protocol was approved by the school and by the local ethics committee. Only right-handed participants were included for brain organizational reasons (Isaacs et al., 2006). Handedness was assessed with the "Edinburgh Handedness Inventory" (Oldfield, 1971; mean score 87.3 ± 16.7). According to reporting of the parents, all children possessed normal hearing and had no history of neurological illnesses. Of the 15 final participants, 10 children did not receive any extra-curricular musical training, 5 practiced musical instruments for 2.8 ± 0.5 years; one played the cello, two the flute and two the piano. Intra-curricular music lessons at public schools in the French speaking part of Switzerland are not strictly protocolled and differ strongly as a function of the teacher. Thus, some explicit knowledge of musical scales may have been provided to the non-musician children.

General procedure

All children were tested twice. At first the children accomplished a musical violation discrimination test while continuous EEG was recorded (see Experimental procedure I: EEG). On average 3 days later (SD: 5 days), the children passed 2 additional behavioral tests in the following order:

1) Raven's "standard progressive matrices" (SPM; Raven et al., 1998)
2) "Digit span" of the Wechsler Intelligence Scale for Children (Wechsler, 2005)

We applied those tests aiming to evaluate possible relationships between short-term memory (Digit span forward), working memory (Digit span backward), fluid intelligence (Raven's) and musical violation discrimination.

Experimental procedure I: EEG

Musical violation discrimination task

We presented 78 original polyphone expressive musical stimuli at two levels of musical transgression at musical closure: regular and harmonically[1] transgressed endings. The original stereo sound-files were converted to single track/mono stimuli in order to cancel out any left ear versus right ear differences and presented binaurally via EEG compatible headphones. The stimuli (n = 156) were presented in

[1] Musical harmony refers to the use of simultaneous pitches or chords.

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