Musical syntax processing in Broca's aphasia

A proposal for an information theory-based experiment

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Abstract
The Shared Syntactic Integration Resource Hypothesis (SSIRH; Patel, 2003) argues that resources for syntactic processing are shared by language and music. As previous models of Broca's aphasia, most notably Avrutin (2006), have claimed that syntactic processing is weakened in Broca's aphasics, this together predicts that Broca's aphasics should not only exhibit problems with the processing of language syntax, but also with musical syntax. In this paper, I propose a new approach for testing this claim based on concepts from information theory (Shannon, 1948). The goal of the proposed experiment is to quantify the severity of the musical deficit of Broca's aphasics with the use of entropy, and find out whether this is correlated with their weakened performance on linguistic syntactic tests. As such, the proposed research could provide a more fine-grained picture of the syntactical deficit of Broca's aphasics in the domain of music and language, and ultimately shed light on the fundamental debate about the modularity of mind.

1. Introduction

Of the many ways human beings can express themselves, two abilities stand out for their striking similarity: language and music. Both are universal cognitive capacities (Patel, 2003); like language, the production (e.g. humming "well-formed", natural sounding melodies) and comprehension (e.g. being able to hear that a certain melody has reached its natural endpoint) of music can be acquired by anyone, with the exception of those who suffer from certain disorders.[1] In both cases, this ability is not explicitly learned, but mostly acquired through regular exposure, resulting in a large amount of implicit knowledge (Ettlinger, Margulis & Wong, 2011; Pesetsky, 2007; Sloboda, 1993). This knowledge is organized in structurally similar ways in language and music. Both systems are rule-governed (Pesetsky, 2007): through the application of syntactic rules, discrete elements, such as words or musical tones, are placed in larger, potentially complex, hierarchical structures that contain multiple levels of organization, such as phrases and sentences, or chords and keys (Patel, 2003, 2008; Pesetsky, 2007).

1 In this paper, musical ability does not refer to explicitly learned musical skills (e.g. being able to play the piano), but rather the implicit musical knowledge that allows us to "make sense of music" (Sloboda, 1993). This is, among other things, demonstrated by our ability to judge whether a melody sounds natural or logical given the rules of a tonal system (e.g. Western music), or the ability to assign a certain emotion to a piece of music. For an introduction, see Sloboda (1993).

One way of exploring the potential overlap between music and language is to study patient groups that have processing problems in one of these two domains, and observe how they behave in the other domain. This is indeed the approach I will take in this article, by proposing an information theory based experiment that tests the musical syntactic abilities of patients with Broca's aphasia.

2. Theoretical background

2.1 The language-music paradox

Different research approaches to the relationship between the syntactic processing of language and music have so far led to interesting, yet paradoxical results (Patel, 2003). On the one hand, neurocognitive studies have strongly suggested an overlap. Patel, Gibson, Ratner, Besson and Holcomb (1998) have, for example, looked at the similarity between language and music processing by testing the domain-specificity of the event-related brain potential (ERP) component P600. The P600 is normally argued to reflect linguistic processing difficulties that arise when incoming words are hard to integrate in the syntactic structure that the listener is building (Patel et al., 1998). However, Patel and his colleagues found that the P600 component was not only elicited by ill-formed sentences, but also when participants heard out-of-key chords in melodic sequences (i.e. chords that are highly unexpected given the musical context). Further analyses revealed that these two P600 components were indistinguishable in terms of amplitude and scalp distribution, suggesting that the P600 is elicited by a process that is not language-specific but common to both language and music.

In another EEG study, Koelsch, Gunter, Wittfoth and Sammler (2005) simultaneously exposed participants to language and music: sentences were presented on a screen while chord sequences were presented over headphones. Crucially, the final word of each sentence made the sentence grammatical or ungrammatical, and was accompanied by either an expected chord (the tonic) or a highly unexpected, out-of-key chord (according to the system of Western tonal music). Interestingly, it was found that linguistic syntax and musical syntax interacted: the early left anterior negativity (LAN) component that was elicited by ungrammatical sentences was reduced in amplitude when the final word was presented with an out-of-key chord. Moreover, a second experiment showed that it was not the case that the LAN is reduced by any type of co-occurring deviance, such as deviant beeps. The authors therefore concluded that the neural resources for music and language syntactic processing must be shared: on exposure to an unexpected chord, these shared resources are already partially used up, which results in less available resources for the generation of the LAN component when the grammatical anomaly is detected in the sentence.

Lastly, fMRI studies show that Broca's and Wernicke's area, both usually associated with language, are also involved in music (e.g. Koelsch, Gunter, Cramon, Zysset, Lohmann & Friederici, 2002; Koelsch, 2006). To sum up, neurocognitive studies support the idea that language and music syntactic processing overlap by showing that both processes interact in the brain.

On the other hand, neurological research has suggested quite the opposite: approximately 5% of the population suffers from congenital or acquired amusia, i.e. tone deafness (Peretz & Hyde, 2003), yet, in most cases, these people do not suffer from any linguistic disabilities (Peretz, 1993). Conversely, there are reported cases of patients with aphasia that do not seem to suffer from amusia, such as the case of a famous composer who continued writing well appreciated music despite suffering from aphasia (Luria, Tsvetkova & Futer, 1965). Evidence from physiological studies thus seems to suggest a double dissociation between language and music capacities.

Patel (2003) has tried to reconcile these paradoxical findings within his Shared Syntactic Integration Resource Hypothesis (SSIRH). This hypothesis assumes a dual system of syntax in which a distinction is made between syntactic representations and syntactic integration (or processing). Music and language clearly differ on the level of syntactic representations, where discrete symbols are stored and manipulated. The level of syntactic integration is where Patel (2003) hypothesizes the overlap between music and language to be. On this level, incoming symbols are connected with each other, and into a syntactic structure. According to the SSIRH, music and language share the neural areas and operations that provide the necessary resources for syntactic integration.

This hypothesis correctly predicts the neurocognitive overlap that the previously mentioned studies observed. Moreover, it can also explain part of the double dissociation between language and music that is sometimes observed in patients. Patel (2003) argues that cases of amusia without aphasia are simply cases where the syntactic representations of music, i.e. tones, are not well-developed or damaged, but the syntactic integration resources are still intact. Cases of aphasia without amusia, on the other hand, are more problematic for the hypothesis. However, Patel (2003) notes that the few reported cases that exist in the literature are all quite outdated and remarkably always concern highly professional musicians. Furthermore, none of these studies have performed systematic testing of musical syntactic abilities. Patel (2003) thus concludes that cases of aphasia without amusia are exceptions.

An interesting test case for the SSIRH would be observing individuals who suffer from syntactic processing problems in either the domain of music or language and observe how they behave in the other domain. Contrary to the older case studies, the SSIRH predicts that a problem with syntactic processing in one domain should always be visible in the other domain as well. A potential patient group to study with this approach would be patients with Broca's aphasia, who experience difficulties with the production and comprehension of linguistic syntax.

2.2 A model of Broca's aphasia (based on Avrutin, 2006)

Patients with Broca's aphasia have usually suffered a stroke in the left posterior and lower frontal lobe of the brain, in and around Broca's area. Broca's aphasics commonly have word retrieval difficulties, and often only produce short sentences in which (some) grammatical elements are lacking. They also usually exhibit difficulties with comprehension, particularly of complex syntactic structures (Pratt & Whitaker, 2006).

Recently, Avrutin (2006) proposed a new model for Broca's aphasia. Central to this model is the claim that Broca's aphasics do not suffer from damage on the level of linguistic representations, and do not lack knowledge of words or grammatical rules. Instead, Avrutin (2006) proposes that damage to Broca's area leads to weakened resources for syntactic computations. According to this model, the so-called morpho-syntactic channel in Broca's aphasics is weakened. Contrary to healthy adults, for whom the use of this channel is the most economical way to encode a message, Broca's aphasics will resort to other available, "cheaper" options than morphosyntax to encode parts of a message. For example, Broca's aphasics are known to often omit grammatical tense markers. In these cases, they use the "cheaper" option of using the pragmatic context or adverbs to express temporal relations.

Like Patel (2003), Avrutin (2006) thus assumes a dual system of syntax in which a distinction is made between representations and integration or processing. Moreover, according to Avrutin (2006) it is the level of syntactic integration, which according to the SSIRH is shared between language and music, that is weakened in Broca's aphasia. Hence, these theories combined predict that Broca's aphasics should also have problems with musical syntactic integration.

Avrutin's model of Broca's aphasia can be quantified and thus tested by making a connection with information theory. Information theory is a mathematical theory of the amount of information that a message contains (Shannon, 1948). One of the central ideas of this theory is that the channel through which information is transmitted has a limit to the amount of information that it can transmit; this is termed the channel capacity. A message can only be transmitted successfully, i.e. without errors, if the amount of information in the message does not exceed the channel capacity (Gregory, 2006).

The amount of information and the channel capacity are usually computed by means of entropy, measured in bits per second. Entropy is a measure of the uncertainty of a set of items, e.g. words or notes, and hence, of the complexity of that set. If the amount of items in the set increases, entropy will increase. Moreover, the more equal the distribution of the relative frequencies of all items is (e.g. all items occur equally often), the higher the entropy will be (Rădulescu, Wijnen and Avrutin, in prep.).

Building on this view and the SSIRH (Patel, 2003), I hypothesize that the morpho-syntactic channel is responsible for both the processing of language and music syntax and is weakened in Broca's aphasia. That is, the channel does not allow for the same level of entropy to be transmitted compared to healthy controls. As a result, these patients will experience processing difficulties in both language and music at a lower level of syntactic complexity, as measured by entropy, than healthy controls.

The goal of the proposed experiment is to test this by first determining whether the channel capacity for musical syntax is weakened in Broca's aphasics, and then finding out whether this is correlated with their weakened performance on linguistic syntactic tests.

There is already some evidence that Broca's aphasics do suffer from a musical syntactic deficit. In two harmonic priming studies, participants heard a sequence of two chords, and had to judge whether the second chord was mistuned or not. Healthy participants showed significantly faster reaction times when the second chord was harmonically close to the first chord according to the system of Western tonal music, than when it was distant. However, aphasics did not show such a priming effect and were sometimes faster on chords that were distant from the first chord according to the system of Western tonal music (i.e. the circle of fifths), but similar to it in an absolute sense, for example by being half a note higher (Patel, Iversen & Hagoort, 2004; Patel, 2005). Furthermore, Patel, Iversen, Wassenaar and Hagoort (2008) showed that Broca's aphasics were significantly less able to find an out-of-key chord in a sequence of chords compared to healthy controls. Moreover, their performance on this task correlated with their performance on linguistic syntactic tests.

One of the shortcomings of these previous experiments, that the proposed experiment will address, is that participants were previously exposed to only two levels of syntactic complexity: highly expected, in-key chords, and completely unexpected, out-of-key chords. By using entropy to quantify different levels of syntactic complexity, the current experiment will be able to provide a more fine-grained picture of the possible musical deficit of Broca's aphasics and see whether the severity of this deficit correlates with the severity of the linguistics deficit.

3. Method

An altered version of the melody-discrimination task as developed by Francès, Lhermitte and Verdy (1973) will be used. In this task, participants judge whether two melodies in a pair are identical or not. Brown and Martinez (2007) previously found that Broca's area is activated during the melody discrimination task, which supports the choice for this test as a measure of musical syntactic comprehension.

3.1 Participants

At least twenty patients officially diagnosed with Broca's aphasia will be recruited to participate in the study. The sentence-picture matching task by Wassenaar, Brown, and Hagoort (2004) will be used to test the severity of their syntactic, linguistic deficit. Additionally, twenty healthy controls, preferably matched by age, musical skill, as measured by the Gold MSI (Müllensiefen, Gingras, Musil & Stewart, 2014), and education, will be recruited. For both groups, participants with absolute pitch, and hearing or working memory impairments will be excluded.

3.2. Stimuli

48 isochronous melodies (i.e. melodies in which all notes are of equal length) will be randomly composed with the notes of either a major or a minor key. As each key contains seven distinct notes (in one octave), each melody will consist of seven quarter notes and contain at least one occurrence of the tonic note, i.e. the primary note of the key (C in the case of C major etc.). The notes will be played at 60 beats per minute, resulting in melodies of approximately 7 seconds. As there are 24 musical keys, there will be two melody pairs

per key. In half of the cases, the two melodies in a pair will be identical ("identical" condition), in the other half they will differ by one note ("different" condition). The differing notes will be distributed evenly over the seven positions of the melodic sequence for the melody pairs in the "different" condition.

The level of entropy will be used as a continuous variable and will be calculated for each melody with the following formula, in which *x* is a note in the melody, and *p(x)* the relative frequency of note *x* in the melody: $H = -\Sigma\, p(x)\, log p(x)$. Recall that entropy, as a measure of complexity, increases when the probability distribution of the items, in this case notes, in a set becomes more equal. When a melody consists of seven different notes, the maximum possible entropy is 2.81. In that case, each note has an equal probability of 1/7. The minimum possible entropy is 0. In that case the tonic is the only note used in the melody and hence has a probability of 7/7 = 1.

An example of a stimulus is given in Figure 1 below. Note that in the "different" condition, the difference is constructed in such a way that the level of entropy is not affected.

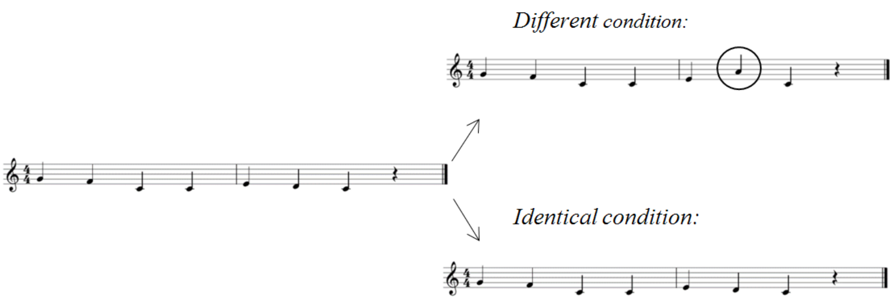

Figure 1. An example of a stimulus. A melody in C major (g f c c e d c) with entropy H = 2.13. The second melody of the pair will either be different (top: g f c c e a c) or identical (bottom: g f c c e d c).

3.3 Procedure

Participants will sit in front of a computer screen while the 48 pairs of melodies will be presented over headphones in a randomized order. During the first melody of a pair, the number one will be displayed on the screen, and during the second, the number two. The two melodies will be separated by a silence of two seconds. After the melody pair has been played, the question "SAME OR DIFFERENT?" is presented on the screen. Participants can then give their answer on a button box. The next pair of melodies will then be played. The task should take approximately 20 minutes to complete.

4. Predictions and expected results

The rationale of the experiment is two-fold. First, it is easier to discriminate two melodies when the listener has integrated the incoming notes of a melody into the structural representation of a key. It has been found by Francès and colleagues (1973) that participants performed significantly better on the discrimination of tonal melodies (i.e. melodies written in the context of a key) than on the discrimination of atonal melodies (i.e. "random" melodies written without a key). Second, I propose that the level of entropy of the melody will reduce the ease with which listeners can construct a musical key.

In order to explain this, some background knowledge about musical keys is required. A key is arranged around one note, the tonic, which is the tonal center. Based on whether the key is minor or major, six additional notes are fundamental to the key (Hyer, 2016). Within a key, not every note is equally important, and therefore not equally frequent. Knopoff and Hutchinson (1983) inspected a large corpus of classical Western pieces of music in major keys and found that the fifth, or dominant, (18%) and the third (16%), the note that determines whether the key is major or minor, were the most frequent, followed by the tonic (16%). Out-of-key notes, like the note a semitone above the tonic, are extremely infrequent (1%), but even some notes that belong to the key, like the sixth (9%), are already much less frequent. Thus, tonal music has an uneven distribution of note probabilities: some notes are very important and frequent, other notes are less frequent and less important. The specific characteristics of this distribution help listeners to determine which key they are hearing.

When the distribution of these probabilities becomes more even, and entropy thus increases, we approach a situation which can ultimately be called atonal, or chance music, in which all twelve notes of Western music occur equally often (Griffiths, 2011). In these cases there is no tonal center or sense of key. So, a continuum from melodies with low entropy to melodies with high entropy is a continuum from very tonal music to completely atonal music.

Based on this idea, I assume that the higher the entropy of a melody, the more difficult it is to integrate the incoming notes into a musical key. When all notes are equally probable, and entropy is high, there is competition between different possible musical keys. For example, when one hears the notes: a d e c f b g (H = 2.81), there is competition between the C major key and the A minor key, as all notes occur in both keys and the equal distribution of note probabilities does not provide clues about the importance of different notes. However, when one hears: g g c c a c c (H = 1.38), there is less competition between the C major key and the A minor key, as the more frequent notes, g and c, help to identify that the it is the C major key that needs to be constructed here. This leads to the first hypothesis:

H1: An increase in entropy will lead to a decrease in performance on the melody discrimination task.

This will show up in the data as a negative effect of entropy on performance (percentage of correct discriminations – percentage of false alarms) in all participants.

Based on the SSIRH (Patel, 2003), and the reasoning outlined above, I expect that the experimental group will overall perform worse than the healthy controls. This leads to the second hypothesis:

H2: Broca's aphasics will perform at chance level on the melody-discrimination task at a lower level of entropy compared to healthy controls.

This would be supported by an effect of group on performance. Finally, I expect that:

H3: The performance of Broca's aphasics on the melody-discrimination task is (positively) correlated with their performance on the sentence-picture matching task.

If these three hypotheses are borne out, this will directly support the SSIRH, and the model of Broca's aphasia by Avrutin (2006), by showing that the capacity of the morpho-syntactic channel of Broca's aphasics is not only weakened in the domain of language syntax but also in the domain of musical syntax, supporting the idea that neural resources for syntactical processing are shared by language and music. The general picture of the expected results can be summarized in the following, idealized figure:

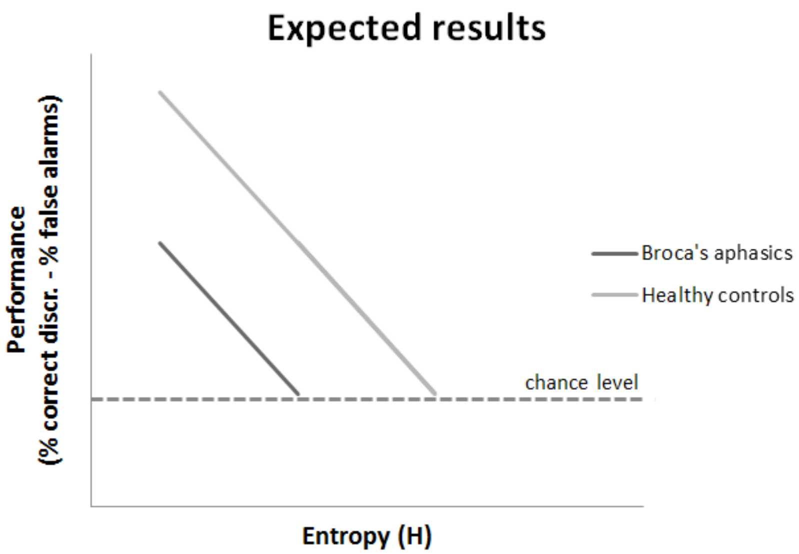

Figure 2. The expected results of the melody-discrimination task.

6. Discussion and conclusion

Combining insights from both the Shared Syntactic Integration Resources Hypothesis (Patel, 2003), Avrutin's model of Broca's aphasia (2006), and information theory (Shannon, 1948) allows us to get a fine-grained idea of the syntactic deficits that Broca's aphasics might have in the domain of music. Although entropy has been used before in the domain of music, this experiment is the first to examine the influence of entropy on musical processing. This, however, also means that the current design will first need to be piloted. Potential pitfalls could be that the melodies are perhaps too long to remember, and that this will lead to discrimination errors that cannot be contributed to the effect of entropy. Furthermore, there could be unforeseen factors that could influence the ease with which participants reconstruct a key out of the incoming notes that the current design does not take into account such as the order of the different notes and the tempo in which the melodies are played.[2]

2 I kindly thank two anonymous reviewers for pointing this out.

Previous research has already looked at the influence of entropy on language processing in both healthy and aphasic populations (e.g. van Ewijk & Avrutin, 2016). Interestingly, whereas I have argued that entropy will inhibit musical processing as an increase in entropy means a decrease in evidence to single out one key, entropy has been found to facilitate comprehension in language. Van Ewijk and Avrutin (2016) argue that in language processing, an even distribution of probabilities means that when a word is encountered, many neighboring words will also be activated and that this will support recognition and processing of the target word. This is an interesting difference between language and music that future research can focus on.

Another interesting path for future research to take would be to test the SSIRH (Patel, 2003) from another point of view, namely by testing patients that only have problems on the representational level of language syntax, and not on the level of integration. If the SSIRH is correct, these patients should not suffer from any musical deficit. A potential group to study in this respect would be patients with semantic dementia, who primarily suffer from the loss of word meanings.

All in all, studying the processing of musical syntax processing in Broca's aphasia is a promising development that can shed light on the overlap between the faculties of language and music, and as such might be of great importance in the debate on the modularity of the mind. ■

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