

## Musical syntactic processing in agrammatic Broca's aphasia

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*Background:* Growing evidence for overlap in the syntactic processing of language and music in non-brain-damaged individuals leads to the question of whether aphasic individuals with grammatical comprehension problems in language also have problems processing structural relations in music.

*Aims:* The current study sought to test musical syntactic processing in individuals with Broca's aphasia and grammatical comprehension deficits, using both explicit and implicit tasks.

*Methods & Procedures:* Two experiments were conducted. In the first experiment 12 individuals with Broca's aphasia (and 14 matched controls) were tested for their sensitivity to grammatical and semantic relations in sentences, and for their sensitivity to musical syntactic (harmonic) relations in chord sequences. An explicit task (acceptability judgement of novel sequences) was used. The second experiment, with 9 individuals with Broca's aphasia (and 12 matched controls), probed musical syntactic processing using an implicit task (harmonic priming).

*Outcomes & Results:* In both experiments the aphasic group showed impaired processing of musical syntactic relations. Control experiments indicated that this could not be attributed to low-level problems with the perception of pitch patterns or with auditory short-term memory for tones.

*Conclusions:* The results suggest that musical syntactic processing in agrammatic aphasia deserves systematic investigation, and that such studies could help probe the nature of the processing deficits underlying linguistic agrammatism. Methodological suggestions are offered for future work in this little-explored area.

**Keywords:** Syntax; Music; Comprehension; Harmony; Language; Aphasia.

This paper examines a little-explored topic—the processing of musical syntactic relations in aphasia. A growing body of evidence from neuroimaging and behavioural research (on non-brain-damaged individuals) points to overlap in the cognitive processing of musical and linguistic syntax (e.g., Koelsch, Gunter, Wittforth, & Sammler, 2005; Patel, Gibson, Ratner, Besson, & Holcomb, 1998;

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Slevc, Rosenberg, & Patel, 2007). This work is related to a specific hypothesis about how linguistic and musical syntactic processing overlap in the brain, a hypothesis that motivates the question of whether aphasic individuals with grammatical comprehension deficits in language also have musical syntactic deficits (Patel, 2003). From the standpoint of aphasiology, this question is relevant to a larger debate over the nature of agrammatism; i.e., whether it reflects damage to specifically linguistic mechanisms or representations, or a more general processing capacity limitation relevant for structural analysis (Grodzinsky, 1990; Kolk, 1998; cf. Grossman, 1980). The answer to this question has both theoretical relevance and clinical implications for the study of language and the brain.

## BACKGROUND

Language and music are human universals that can be compared at many levels (e.g., phonology and syntax). The current focus is on syntax because language and music have intriguing parallels and differences as syntactic systems. A basic parallel is that both domains combine perceptually discrete elements (such as words or tones) in principled ways to form hierarchically structured sequences. Native listeners have implicit knowledge of these syntactic systems, knowledge that requires no formal training and which emerges from a combination of innate constraints and implicit learning of structural regularities (see Tillmann, Bharucha, & Bigand, 2000). In both domains, listeners can demonstrate their syntactic knowledge via judgements of the well-formedness of novel sequences.

Despite these general similarities, it is also clear that musical and linguistic syntax differ in important ways. For example, fundamental grammatical categories in language (such as nouns and verbs) have no analogue in music, and the function of linguistic syntax in indicating “who did what to whom” also has no musical parallel. Instead, (Western) musical syntax is based on selecting a set of seven discrete pitches within each octave and creating a musical “key” by using these pitches in such a way that a hierarchy of structural importance is created among them. This leads to certain pitches and chords being perceived as more stable than others. These stable elements act as cognitive reference points, with one (the tonic note or chord) being the most stable (Krumhansl, 1990). This syntax functions to build patterns of tension and resolution in musical sequences (Lerdahl & Jackendoff, 1983). Thus it is clear that musical syntax is not simply a trivial variant of linguistic syntax.

Nevertheless, musical and linguistic syntax may engage similar cognitive processes at some level, because both require the rapid integration of incoming elements into a network of structural relations that unfolds as sequences are processed in time. In particular, in both domains the difficulty of integrating an incoming element depends on structural relations between the element and the existing sequence. In language, for example, an incoming word is more difficult to process when it is distant from a prior dependent word (i.e., a long-distance syntactic dependency) or when it represents an unexpected syntactic category (e.g., as occurs in garden path sentences) (Gibson, 1998; Levy, 2008). In music, an incoming tone or chord is more difficult to process when it is structurally unexpected in the context of the preceding sequence, such as a chord from a harmonically distant key (e.g., Loui & Wessel, 2007). Notably, neuroimaging studies of language and music have revealed overlap in the brain’s response to difficult syntactic integrations in the two domains (Patel et al., 1998; cf. Maess, Koelsch, Gunter, & Friederici, 2001).

In contrast to this evidence for overlap, research on the neuropsychology of music has provided clear cases of dissociations between linguistic and musical syntactic abilities following brain damage. For example, Peretz (1993) documented a case of a non-aphasic man with bilateral temporal lobe damage (due to strokes) who lost sensitivity to musical key, even though his basic perception of pitch patterns was intact. This is one of several well-documented cases of “amusia without aphasia”. Thus a theoretical framework is needed which can accommodate such evidence as well as evidence for overlap in syntactic processing as discussed in the preceding paragraph. Patel (2003) proposed one such framework based on the idea that language and music have distinct and domain-specific syntactic representations (such as words and their syntactic features in language, and chords and their harmonic relations in music), but that activating these representations as part of online processing draws on a common pool of limited neural resources. This idea was termed the “shared syntactic integration resource hypothesis” (SSIRH). The SSIRH posits that linguistic and musical syntactic representations are stored in distinct brain networks (and hence can be selectively damaged), whereas there is overlap in the networks that provide neural resources for the activation of stored syntactic representations. It is hypothesised that such resources are needed when dealing with difficult structural integrations, because such integrations require the rapid and selective activation of items with low activation levels in representation networks (e. g., structurally unexpected words or chords).

How does this proposal map onto neural architecture? At the moment the answer to this question is not known. In its original formulation, the SSIRH combined the functional proposal outlined above with a rough localisationist proposal, namely that that neural resources reside in frontal brain regions, while syntactic representations reside in posterior regions, and that the two kinds of networks interact via reciprocal neural connections. Patel (2003) noted that testing this proposal required localisationist techniques such as fMRI, applied to within-participants comparisons of syntactic processing in language and music. Such work remains to be done. For the current purposes, the salient point is the functional and localisation aspects of the SSIRH can be conceptually decoupled, and that the SSIRH posits that common resources underlie structural integration in both domains. One prediction of the SSIRH is that simultaneous demanding structural integrations in language and music will lead to interference between the two types of processing; a prediction that has been supported by neural and behavioural research (e.g., Koelsch et al., 2005; Slevc et al., 2007). Another prediction is that individuals with compromised resource networks will exhibit parallel deficits in linguistic and musical syntactic processing. This prediction motivates the study of music syntax processing in agrammatic aphasia, because it has been suggested that agrammatism can be due to a reduction in processing resources for syntactic operations, rather than damage to specific linguistic syntactic mechanisms (see Caplan & Waters, 2006). If this is the case, then the SSIRH predicts that agrammatic aphasic individuals should also have musical syntactic deficits.

#### PRIOR RESEARCH ON MUSICAL SYNTACTIC PROCESSING IN APHASIA

Most research on the musical abilities of aphasic individuals has focused on production rather than perception (and in particular, on the singing abilities of

nonfluent patients; e.g., Racette, Bard, & Peretz, 2006). Of possible relevance to the current work are cases of “aphasia without amusia”, such as the composer Shebalin (Luria, Tsvetkova, & Futer, 1965), who continued to write music after becoming aphasic due to a stroke. Such cases, together with cases of amusia without aphasia, seem to constitute a double dissociation between language and music, and thus obviate any possibility of overlap between linguistic and musical brain processing. However, Tzortis, Goldblum, Dang, Forette, and Boller (2000) point out that all reported cases of aphasia without amusia involve professional musicians. This is a concern because research on neural plasticity has revealed that the brains of professional musicians differ from those of non-musicians in a variety of ways, including increased grey matter density in regions of frontal cortex and increased corpus callosum size (Gaser & Schlaug, 2003). Thus reports of aphasia without amusia in musicians should not deter the study of music syntactic processing in ordinary aphasic individuals. To our knowledge, there is only one prior study of music syntax processing in such individuals (Francès, Lhermitte, & Verdy, 1973). That study suggested that aphasic individuals had difficulty with processing harmonic relations in music. However, it did not measure grammatical comprehension deficits in language, and had a number of other methodological limitations that make the results hard to interpret. Hence there is a need for studies that examine linguistic and musical syntactic processing in aphasia using quantitative methods.

## THE CURRENT STUDIES

Two studies are reported in the current paper. The first examines linguistic and musical syntactic processing using explicit judgements of the acceptability of novel sequences. Linguistic semantic processing was also tested, to check for relationships between musical syntactic processing and linguistic semantic processing. The second study probed musical syntactic processing using an implicit task (harmonic priming, a well-studied paradigm in music cognition). Both studies examine individuals with Broca’s aphasia and agrammatic comprehension.

## EXPERIMENT 1

### Method

*Generic methods.* The following methods were common to Experiments 1 and 2 (and hence are not repeated in the description of Experiment 2): Aphasic participants were classified as Broca’s-type based on the Aachen Aphasia Test (AAT) and on evaluation of transcribed samples of spontaneous speech by three specialists in aphasia. All were pre-morbidly right-handed and all were native speakers of Dutch (none was a full bilingual). None reported any hearing problems. (Note that individuals with such problems would likely have a significantly lower score on the auditory vs written comprehension subtests of the AAT, which was not observed.) Some had played musical instruments as a hobby, but none had been a professional musician. Medical records indicated that all suffered from an ischaemic stroke (CVA) in the left hemisphere. However, the sites of their lesions were variable and did not always include Broca’s area. It is known that Broca’s aphasia and syntactic comprehension deficits are associated with a variable lesion profile, not necessarily

including Broca's region (Caplan, Hildebrandt, & Makris, 1996). Thus the current studies do not address localisation of function, and focus instead on the functional relationship of syntactic comprehension deficits in language and music. Participants in both studies gave informed consent, completed a questionnaire about their musical experience, and were tested in a quiet room at the Max Planck Institute for Psycholinguistics in Nijmegen, The Netherlands.

*Participants.* A total of 12 Dutch-speaking aphasic persons (mean age 58.8 y, range 44–72,  $SD = 9.6$ , 3 female, at least 13 months post-stroke) and 14 age- and education-matched controls participated in the experiment. Clinical CT scans were available for most aphasic individuals. Patient characteristics are given in Table 1.

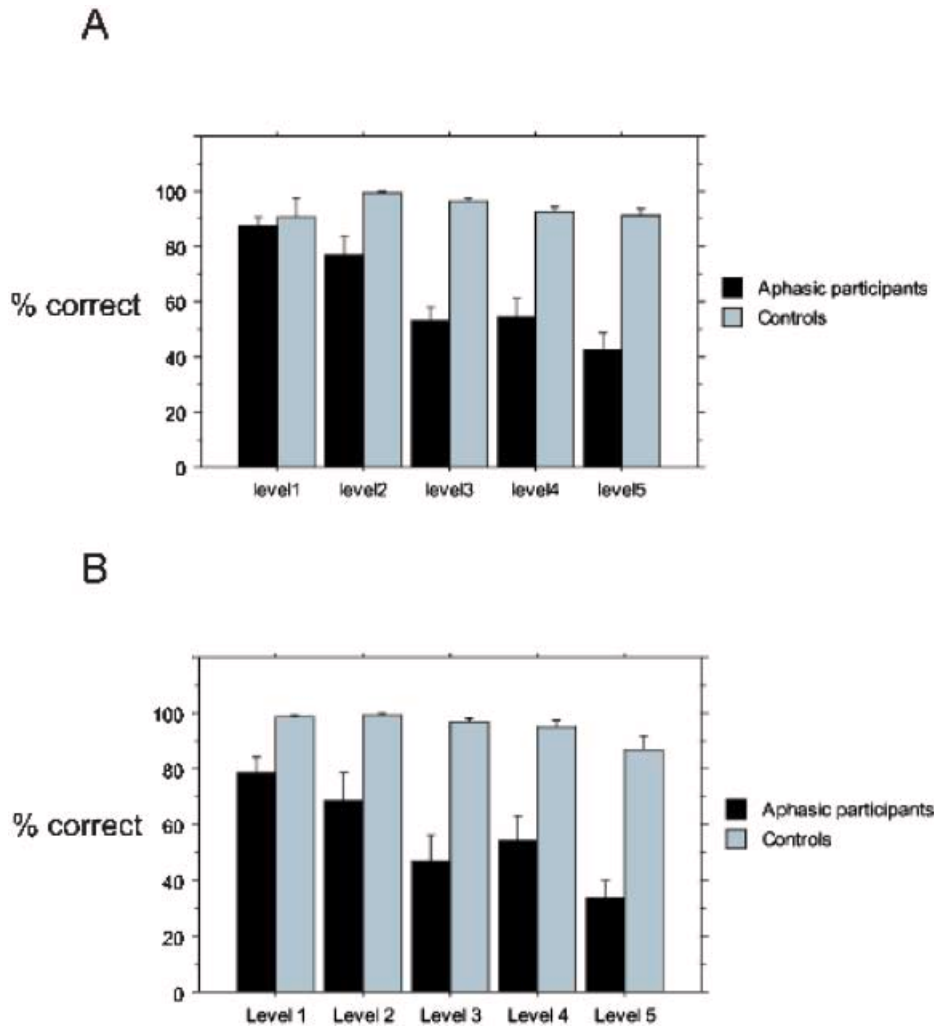
*Language pretest.* To establish that the aphasic individuals had a linguistic syntactic comprehension deficit, a Dutch version of a sentence–picture matching task was administered (see Wassenaar, Brown, & Hagoort, 2004). Participants heard one sentence at a time (e.g., “The girl on the chair is greeted by the man”) and pointed to the corresponding picture on a panel with four pictures. Sentences ranged across five levels of syntactic complexity, from active semantically irreversible sentences to sentences with an embedded subject-relative clause in the passive voice. Correct matching for levels 2–5 could only be done on the basis of syntactic information (e.g., word-order heuristics such as “first noun = agent” would not work). Figure 1A shows the results. (NB: Data from one control participant were not available for this task, hence Figure 1A and its associated statistics represent data from 13 controls.)

A repeated measures ANOVA with group (aphasic participants, controls) as a between-participants factor and level of complexity (1–5) as a within-participants

TABLE 1  
Aphasic participant characteristics, Experiment 1

<i>Age</i>	<i>Sex</i>	<i>Lesion localisation (clinical CT scan)</i>	<i>Musical training</i>	<i>AAT Language comprehension (max = 120)</i>
44	M*	Left fronto-temporo-parietal, including insula	Amateur choir	67
47	M	Left temporo-parietal	None	94
50	M	Left parieto-occipital	None	84
52	M	Left temporo-parietal	Amateur accordion and choir	89
54	F	Left fronto-temporo-parietal, including insula	None	97
59	M	Left internal capsule	None	111
59	M*	Left basal ganglia and parietal	None	83
60	M	Left frontal, some parietal	None	95
68	F	Left fronto-temporal, including insula	None	91
69	F	No adequate information available	Amateur guitar	103
71	M	Left fronto-temporal, including insula	Amateur clarinet	83
72	M	Left temporal	None	89
Mean				Mean ( <i>SD</i> )
( <i>SD</i> )				
58.8 (9.6)				90.5 (11.1)

\* = Data excluded due to low score on music pretest.



**Figure 1.** Performance on the sentence–picture matching task as function of syntactic complexity (level 5 most complex). (A) Data for Experiment 1. (B) Data for Experiment 2.

factor revealed a main effect of participant group,  $F(1, 23) = 41.56, p < .0001$ , and an interaction with level of complexity,  $F(4, 92) = 13.14, p < .001$ : aphasic participants performed significantly worse than controls, with the difference increasing as sentences became more complex. Thus the aphasic individuals had a syntactic comprehension deficit in language.

*Music pretest.* To check for possible basic pitch perception or memory problems, participants were given a subtest from the Montreal Battery of Evaluation of Amusia (Peretz, Champod, & Hyde, 2003). Participants were presented with pairs ( $n = 30$ ) of short unfamiliar melodies for same/different discrimination. Members of a pair were either identical or differed by a single note. In the latter case, the change was made in a manner that preserved the melodic contour but violated the key of the melody. Hence correct discrimination required the ability to encode and remember

specific pitch interval patterns, rather than simply remembering the global shape or contour of a melody. Two aphasic and one control participants performed at chance on this test, and were excluded from further analyses. The mean and *SE* of percent correct for the remaining aphasic and control participants was 79.4 (2.6) and 81.6 (2.7), respectively,  $t(21) = -.57, p = .57$ , unpaired *t*-test, showing that the two groups did not differ on basic pitch discrimination or memory skills.

*Main experimental tasks.* For the linguistic task, participants listened to 120 pre-recorded experimental sentences. After each sentence, participants had to decide whether the sentence was correct or had some kind of error in it. The sentences belonged either to a syntactic or semantic condition. The syntactic condition consisted of 60 sentences with a conjoined syntactic structure: half were syntactically correct, and half contained a violation of subject–verb number agreement between the first noun and the second verb, for example:

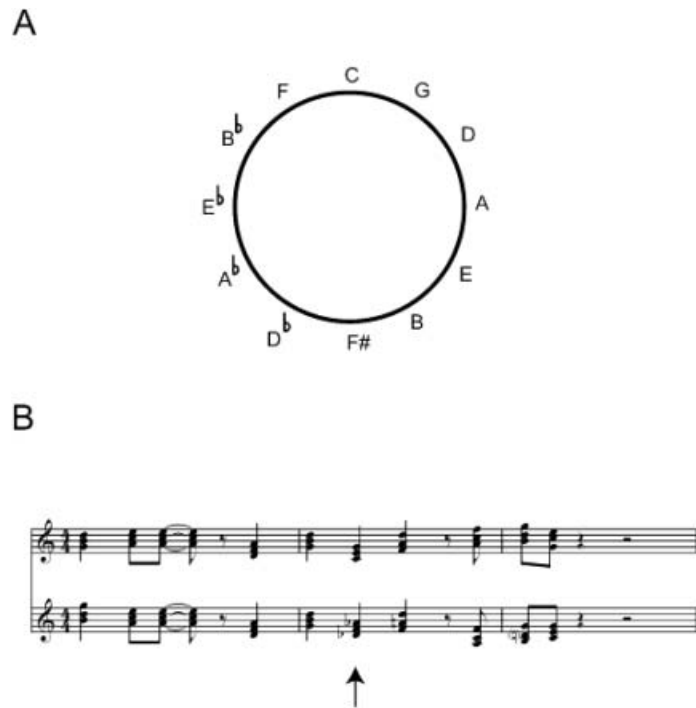
- (1) De matrozen roepen de kapitein en eisen een lekkere fles rum.  
The sailors call for the captain and demand a fine bottle of rum.
- (2) De matrozen roepen de kapitein en eist een lekkere fles rum.  
\*The sailors call for the captain and demands a fine bottle of rum.

The semantic condition also consisted of 60 sentences: half were semantically normal and half contained a semantic violation in mid-sentence position, for example:

- (3) Jan had een gat in zijn broek na zijn sprong over het hek.  
John had a hole in his trousers after a jump over the fence.
- (4) Anne kraste haar naam met haar tomaat in de houten deur.  
Anne scratched her name with her tomato on the wooden door

Sentences from the syntactic condition had been used in a previous ERP study of agrammatic Broca’s aphasia (Wassenaar et al., 2004). Sentences from the syntactic and semantic conditions were interleaved in a pseudo-random order and divided into two blocks of 60 sentences each (for the syntactic condition, members of a grammatical–ungrammatical pair were placed in separate blocks). The order of these blocks was counterbalanced across participants.

For the musical task, participants listened to 60 chord sequences that had been created with MIDI using a grand piano timbre. After each sequence, participants had to indicate whether the sequence was acceptable or not, defined as “whether or not all consecutive tones belonged together in a musical sense”. The sequences (taken from the ERP study of Patel et al., 1998, and available upon request) were pop-style chord progressions that clearly established a musical key and followed harmonic patterns characteristic of Western European tonal music. Sequences ranged in length from 7–12 chords in length and lasted 5.7 seconds on average (range 3.5–8 s, tempo 120 bpm). In half of the sequences all chords adhered to a single major key. In the other half, an out-of-key chord occurred within the phrase and created a syntactic anomaly. This chord was always at least five chords into the phrase (i.e., after a well-developed sense of key had built up), and never less than two chords from the end. This chord was harmonically distant from the rest of the phrase as defined by the circle of fifths, a music-theoretic device for measuring the harmonic distance between musical keys (Figure 2).



**Figure 2.** (A) The circle of fifths for musical keys. Each letter indicates the principal or tonic note/chord of a musical key. The perceived relatedness of two keys decreases with increasing distance between the keys along the circle. (B) Example musical phrases used in Experiment 1. In the upper phrase, all chords are from the key of C major. The lower phrase is also in C major, except that the chord marked by an arrow is the principal (tonic) chord of D-flat major, the key five counterclockwise steps away on the circle of fifths.

Specifically, out-of-key chords were always the principal (or “tonic”) chord of the key five counterclockwise steps away from the key of the phrase (see Patel et al., 1998, for further stimulus details). Sequences were presented in a single block in pseudorandom order such that no more than three sequences with (or without) harmonic anomalies occurred in a row.

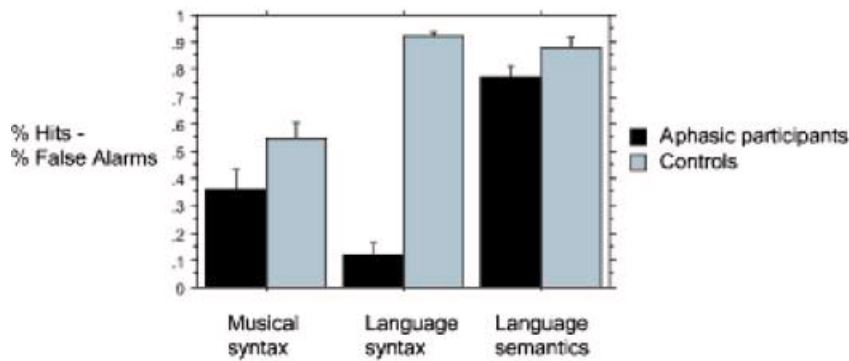
Participants completed the tasks in a fixed order, with the music test preceding the language test. Breaks were given between tasks and blocks, and practice items were given before each task. Feedback was given during the practice items but not during the main tests. There was no explicit time limit for responding, but during the instructions participants were encouraged to respond directly after hearing each stimulus (RT data were not collected). Participants heard all stimuli over closed-ear headphones (Sennheiser HD-224) at a comfortable listening level. A second set of headphones was worn by the experimenter. Responses were indicated verbally. The aphasic participants were also allowed to indicate their response by pointing to a word or image on a response sheet, if desired.

## Results

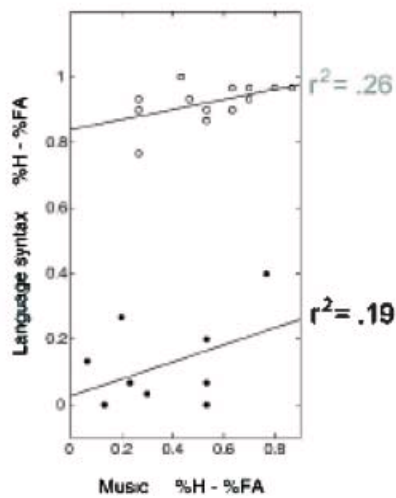
Figure 3A shows the results on the chord sequence (musical syntax) task and on the two linguistic tasks (syntax and semantics).



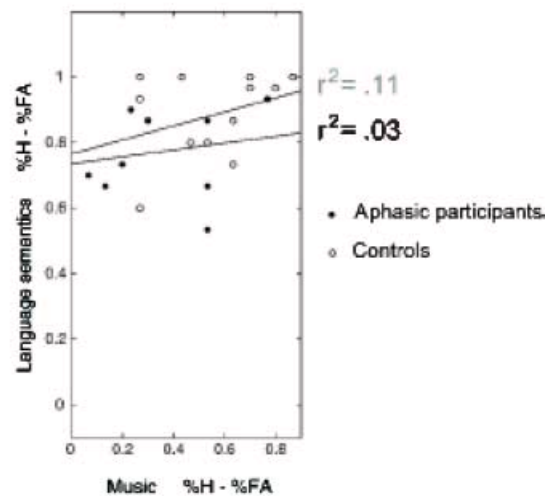
A



B



C



**Figure 3.** (A) Performance on the music syntax task and on the two language tasks (syntax and semantics). (B), (C) Relationship between performance on the music syntax task and (B) the language syntax task or (C) the language semantic task. Hierarchical regression  $r^2$  values are shown for aphasic participants (in black) and controls (in grey) in each panel (see text for  $p$  values). Both axes show %Hits – % False Alarms. Regression equations: *Syntax*: Aphasic participants: Language =  $.03 + .26 * \text{Music}$ ; Controls: Language =  $.84 + .15 * \text{Music}$ . *Semantics*: Aphasic participants: Language =  $.74 + .10 * \text{Music}$ ; Controls: Language =  $.77 + .21 * \text{Music}$ .

Performance was measured as % hits – % false alarms. A hit was defined as an anomalous sequence classified as such, while a false alarm was a normal sequence classified as anomalous (the maximum score is thus 1, and random guessing yields a score of 0 on average). Aphasic–control comparisons were analysed independently for the three tasks using unpaired  $t$ -tests. Of primary interest for the current study, aphasic participants showed a deficit in detecting harmonic anomalies in chord sequences,  $t(21) = -2.11$   $p < .05$ , suggesting a musical syntactic deficit. As predicted,

they performed worse than the controls on the linguistic syntactic task,  $t(21) = -19.61$ ,  $p < .001$ , confirming that they had deficits in linguistic syntax. The aphasic participants also performed worse than controls on the semantic task, though this difference was marginally significant,  $t(21) = -2.00$ ,  $p = .06$ .

The fact that aphasic individuals showed both syntactic and (marginally significant) semantic deficits in language raised the question of the specificity of a link between musical and linguistic syntax. To address this issue, correlations were examined between the aphasic participants' performance on the musical syntax task and on the two language tasks. This revealed non-significant correlations between performance on the musical syntax task and on both language tasks ( $r^2 = .19$ ,  $p = .21$  for the language syntax task and  $r^2 = .03$ ,  $p = .63$  for the semantic task). To probe these relations further, the performance of the controls was added to the analysis. This increased the power of the statistical analyses and was motivated by the fact that the SSIRH suggests a relationship between linguistic and musical syntactic processing in non-brain-damaged individuals. To conduct these analyses in a proper statistical fashion, simple correlations were replaced by hierarchical regressions of linguistic performance on musical performance. In these regressions, the presence or absence of aphasia was coded as a categorical (dummy) variable, so that relations between performance on the language and music tasks could be considered independently of the mean level of performance on the language task.

The results of these regressions are shown in Figure 3B,C ( $r^2$  values shown in inset, see caption for regression equations). Performance on the music syntax task was a significant predictor of performance on the language syntax task (Figure 3B,  $t = 2.20$ ,  $p = .04$ ). In contrast, performance on the music task did not predict performance on the language semantics task (Figure 3C,  $t = 1.21$ ,  $p = .24$ ). This suggests that there is some process common to language and music syntax in both controls and aphasic individuals, but which is operating less effectively in the aphasic individuals.

## EXPERIMENT 2

### Method

*Participants.* A total of 9 Dutch-speaking participants with Broca's aphasia (mean age 60.1 years, range 47–72,  $SD = 7.9$ , 4 female, at least 9 months post-stroke) and 12 age- and education-matched controls participated in the experiment. Four of the aphasic participants had participated in Experiment 1. Clinical CT scans were available for most aphasic individuals. Patient characteristics are given in Table 2.

*Language pretest.* The sentence–picture matching task was once again used to establish a linguistic syntactic comprehension deficit (see Experiment 1 pretest). Figure 1B shows the results. A repeated measures ANOVA with group (aphasic participants, controls) as a between-participants factor and level of complexity (1–5) as a within-participants factor revealed a main effect of participant type,  $F(1, 19) = 37.16$ ,  $p < .0001$ , and an interaction with level of complexity,  $F(4, 76) = 8.76$ ,  $p < .001$ : aphasic individuals performed significantly worse than controls, with the difference increasing as sentences became more complex. Thus the aphasic individuals had a syntactic comprehension deficit in language.

TABLE 2  
Aphasic participant characteristics, Experiment 2

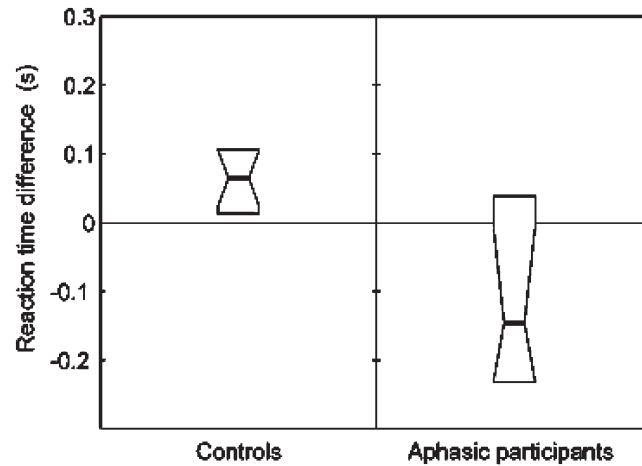
Age	Sex	Lesion localisation (clinical CT scan)	Musical training	AAT Language comprehension (max = 120)
47	F	Left frontal (including posterior limb of internal capsule) and parietal	Amateur trumpet	94
51	M*	Left temporo-parietal	None	94
56	M*	Left temporo-parietal	Amateur accordion and choir	89
57	F	No adequate information available	None	100
63	M*	Left internal capsule	None	111
64	M*	Left frontal, some parietal	None	95
65	F	No adequate information available	Amateur piano	102
66	M	No adequate information available	Amateur trumpet	86
72	F	Fronto-temporal, including basal ganglia	Amateur banjo	65
Mean (SD)				Mean (SD)
60.1 (7.9)				92.9 (12.8)

\*= Individual also participated in Experiment 1.

*Music pretest.* The aphasic participants completed two short pretests relevant to the main experimental tasks. The first tested the ability to discriminate tuned from mistuned chords, and the second tested auditory short-term memory. In the latter task, one pair of chords was presented at a time and participants had to decide if members of the pair were the same or different (each chord in the pair was 1 second long, and they were separated by 1 second). Aphasic participants performed as well as controls on these tasks, indicating no low-level deficits that would influence the main task.

*Main experimental tasks.* The main experiment utilised harmonic priming, which tests the influence of a preceding harmonic context on the processing of a target chord (Bharucha, 1987). Much research has shown that a target chord is processed more rapidly and accurately if it is harmonically close to (vs distant from) the tonal centre created by the context. Importantly, this advantage is not simply due to the psychoacoustic similarity of context and target, but to their distance in a structured cognitive space of chords and keys. The harmonic priming effect thus indicates implicit knowledge of syntactic conventions in tonal music, and has been repeatedly demonstrated in non-musician listeners in Western cultures.

This experiment used a version of the harmonic priming task modelled on the study of Tekman and Bharucha (1998) in which the context is a single chord (which is thought to activate a sense of key, see Bharucha, 1987). Prime and target chords were 1 second long each, separated by 50 ms. The harmonic distance between prime and target was regulated by the circle of fifths for musical keys: Harmonically close versus distant targets were two versus four clockwise steps away from the prime on the circle, respectively (e.g., for a C-major prime chord [tones c – e – g], the close and distant targets were a D-major [tones d – f# – a] and an E-major chord [tones e – g# – b], respectively, see Figure 2). This directly pits conventional harmonic distance against psychoacoustic similarity, because the distant target shares a common tone with the prime.



**Figure 4.** Box plots for RT difference to harmonically distant – harmonically close targets. Data are for correct responses to tuned targets. The horizontal line in each box indicates the median value, slanted box edges indicate confidence intervals, upper and lower bounds of the box indicate interquartile ranges. Absolute mean RTs for controls (*SE* in parentheses): close targets .99 (.07) s, distant targets 1.05 (.06) s. For aphasic participants: close targets 1.68 (.22) s, distant targets 1.63 (.17) s.

Participants heard 48 pairs of chords (12 primes [one for each major key]  $\times$  2 target distances  $\times$  2 tuning levels) in a different random order over headphones. As is common in priming studies, all chords were major triads built from Shepard tones (frequency range 78–2350 Hz), and thus had an organ-like quality and were ambiguous in terms of pitch height, to focus attention on harmonic relations rather than on the direction of pitch movement between chords (voice-leading). The task was to judge whether the second chord was tuned or mistuned (on 50% of the trials, it was mistuned by flattening the upper note of the triad by .35 semitones). The experiment was controlled by Presentation software, and feedback was given after each response via the computer screen. The main focus of interest was reaction time (RT) to well-tuned targets as a function of their harmonic distance from the prime. A faster RT to close versus distant chords is evidence of harmonic priming.

## Results

The results are shown in Figure 4. Controls showed normal harmonic priming, with faster reaction times to harmonically close versus distant well-tuned targets ( $p = .02$ , all  $p$ -values reported in this paragraph were computed using the Wilcoxon Signed Rank test). Aphasic participants, however, failed to show a priming effect ( $p = .31$ ), and even showed a non-significant trend to be faster on distant targets, suggestive of responses driven by psychoacoustic similarity rather than by harmonic knowledge. Harmonic distance did not influence accuracy for classifying chords as tuned or mistuned—mean and *SE* of % error, controls: close 11.6% (3.9) distant 11.1% (3.5),  $p = .72$ ; for aphasic individuals: close 14.8% (5.2), distant 8.3% (3.1),  $p = .35$ .

## DISCUSSION

The results of the current studies suggest that agrammatism in Broca's aphasia is not strictly a linguistic deficit, but also influences the processing of structural relations in

other domains. That is, ordinary individuals with Broca's aphasia and syntactic comprehension deficits in language also appear to have difficulty in processing the harmonic syntax of Western tonal music. This is consistent with the shared syntactic integration resource hypothesis (SSIRH), and with the idea that these aphasic individuals have diminished processing resources for structural integration in both domains.

It should be noted, however, that the musical deficits observed in the current studies were relatively mild compared to the linguistic syntactic deficits. This could reflect methodological limitations of the current work. Thus further research is needed to better investigate links between linguistic and musical agrammatism. Such work can benefit from a number of methodological improvements over the current studies. First, it would be desirable to test patients with more uniform (anterior) lesion profiles, based on data from structural and metabolic neuroimaging. Second, it would be worth probing different kinds of linguistic syntactic operations. There is no theoretical reason to believe that the particular linguistic syntactic task used in the Experiment 1, based on detecting subject–verb agreement in a long-distance dependency, is the best for probing relations between linguistic and musical syntactic processing. Many other language tasks could be used to manipulate structural integration difficulty, and it would be interesting to discover which kinds of linguistic tasks do (vs do not) correlate with performance on musical syntactic tasks. More broadly, it would be interesting to determine whether performance on musical syntax tasks correlates only with performance on language syntax tasks, or with other measures of language comprehension.

Third, it would be worth comparing online measures of syntactic processing of language and music in aphasia (e.g., using ERPs or behavioural techniques), in addition to offline measures of the type used here. Finally, future work would benefit from matching the difficulty of syntactic tasks across domains, to better determine the degree to which abilities in one domain predict abilities in the other.

Taking a step back, the current results suggest that the time has come to study music perception in aphasia, an area that is virtually unexplored. There is theoretical motivation for such work, and tasks and stimuli from the field of music cognition are ready to be applied to this issue. Indeed, the field of aphasiology is in a position to make fundamental contributions to the study of music-language relations in the brain, and hence to improve our understanding of the nature of linguistic disorders.

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