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Relationship between musical and language abilities in post-stroke aphasia

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ABSTRACT

Background: The relationship between structural processing in music and language can be viewed from two perspectives: whether the neural processing of music and language recruits shared neural resources, and whether musical ability is associated with neuroplastic resilience against language impairment.

Aims: This study investigated music and language processing in persons who developed aphasia (PWA) following left-hemisphere stroke, and asked three questions: (1) whether musical structure processing is compromised in PWA, (2) whether there is a relationship between the processing of musical and linguistic structure, and (3) if prior musical ability is associated with post-stroke music and language task performance.

Methods & Procedures: Procedures included four computer-based tasks of sensitivity to structure in music and language, testing of general language impairment, and questionnaires on musical sophistication in 23 PWA.

Outcomes & Results: This study found that PWA's processing of musical structure was unimpaired relative to neurotypical controls. This was also the case for individuals with agrammatic aphasia, who have a specific deficit in syntactic formulation. Second, music and language structural processing performance was not correlated in the healthy or aphasic group. Third, in PWA, prior musical ability correlated positively with implicit structural processing of music and language, and negatively with aphasia severity. The relationship between musical ability (years of music lessons) and aphasia severity was stronger when combined with an additional group of 15 PWA.

Conclusions: These findings suggest that while structural processing of music and language is dissociated in neurotypical individuals and in those with left-hemisphere damage, there may be a potential for neuroplastic effects of musical training on language impairment.

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Introduction

The relationship between musical ability and language has drawn interest from various disciplines. It informs mechanisms underlying, cognitive processing, cognitive reserve, and the potential for neurorehabilitation. Musical training in children and adults is associated

with superior performance in many language tasks, such as processing linguistic pitch (Besson, Schon, Moreno, Santos, & Magne, 2007; Wong, Skoe, Russo, Dees, & Kraus, 2007), verbal memory (Ho, Cheung, & Chan, 2003), word learning (Dittinger, Chobert, Ziegler, & Besson, 2017), reading (Moreno et al., 2009), syntactic learning (Brod & Opitz, 2012; Jentschke & Koelsch, 2009), and syntactic processing (Jentschke & Koelsch, 2009; Patel, Gibson, Ratner, Besson, & Holcomb, 1998). Similarly, musical ability (i.e., based on individual differences in musical task(s) performance rather than on formal training) is associated with processing linguistic pitch (Delogu, Lampis, & Belardinelli, 2010) and second-language phonological abilities (Slevc & Miyake, 2006). These relationships can be explained by enhanced auditory processing from musical practice (Patel, 2014; Wong et al., 2007); shared reliance on cognitive control (Slevc & Okada, 2015) or working memory (Fiveash & Pammer, 2014); or similarities in hierarchical structure (Fadiga, Craighero, & D'Ausilio, 2009; Heffner & Slevc, 2015; Patel, 2003). The present study focuses on the structural similarity between music and language.

Music theorists and language scientists have identified several structural parallels between music and language, including hierarchical organization, recursivity, and long-distance dependencies (Patel, 2003; Rohrmeier, 2011). The term “syntax” refers to the sequential structural expectations in language, music, and other domains (Van de Cavey & Hartsuiker, 2016). Patel’s (2003) Shared Syntactic Resource Integration Hypothesis (SSRIH) proposes that both musical and language syntax are processed by the same domain-general cognitive mechanism located in the left frontal lobe, but rely on distinct neural representations in the temporal lobes. Supporting this hypothesis, several empirical investigations have found interactions between musical and linguistic syntax. For example, sentences with syntactic unexpectancies are read more slowly when coupled with music-syntactic violations (harmonically anomalous music; Hoch, Poulin-Charronnat, & Tillmann, 2011; Jung, Sontag, Park, & Loui, 2015; Slevc, Rosenberg, & Patel, 2009). The logic is that computation of linguistic and musical syntax utilizes overlapping neurocognitive resources, leading to a slowdown. While some studies found interference effects for syntactically but not semantically anomalous sentences (Slevc et al., 2009), other studies have found musical interference effects for both syntactically and semantically anomalous sentences (Perruchet & Poulin-Charronnat, 2013). In another paradigm, performance in sentence recall, but not word list recall, declined when participants were presented with musical syntactic violations (Fiveash & Pammer, 2014).

Neuroimaging evidence is also mixed. On one hand, musical and linguistic syntactic processing shows an overlapping electrophysiological time course (e.g., Patel et al., 1998) and musical structure manipulations interact with electrophysiological indices of both syntactic and semantic unexpectancies (e.g., Koelsch, Gunter, Wittfoth, & Sammler, 2005; Steinbeis & Koelsch, 2008). Spatially overlapping neural responses to musical and linguistic structural manipulations have also been found, particularly in the left posterior inferior frontal gyrus (LIFG, Broca’s region) (Chiang et al., 2018; Kunert, Willems, Casasanto, Patel, & Hagoort, 2015; Levitin & Menon, 2003; Musso et al., 2015), and in the bilateral temporal lobe (Sammler et al., 2013). However, some comparisons have failed to find coactivation in the LIFG, both at the group level (Rogalsky, Rong, Saberi, & Hickok, 2011) and in individual participants’ region-of-interest analyses (Fedorenko, Duncan, & Kanwisher, 2012). It is also argued that neural overlap (e.g., Abrams et al., 2011; Kunert et al., 2015) does not necessarily entail shared neural processing (Peretz, Vuvan, Lagrois, & Armony, 2015). Meta-analyses of

neuroimaging studies have found neural differences between music and language processing, especially for complex tasks (LaCroix, Diaz, & Rogalsky, 2015; Peretz et al., 2015).

Empirical evidence of the relationship between music and language is inconclusive and warrants further research. While numerous studies have examined this question in neurotypical individuals (see reviews by Kunert & Slevc, 2015; Peretz et al., 2015), less is known about this interaction in individuals with unilateral brain lesions. It is unclear if syntactic processing of *both* music and language is impaired, as predicted by SSRIH (Patel, 2003). One case report (Slevc, Faroqi-Shah, Saxena, & Okada, 2016) and one group study (N = 12; Patel, Iversen, Wassenaar, & Hagoort, 2008) manipulated structural violations of music and language in individuals with left-hemisphere damage with syntax-specific language impairments (agrammatic aphasia). While Slevc et al. (2016) found preserved musical processing, Patel et al. (2008) reported impaired musical processing. Although these findings appear contradictory, it should be noted that Slevc et al.'s (Slevc et al., 2016) patient was an amateur musician, possibly giving her a greater cognitive reserve for musical processing. Moreover, Patel et al. found no significant correlation between the extent of language and musical impairment, weakening their argument of shared neural processing.

There are also cases of PWA (not necessarily agrammatic) who show spared musical processing (e.g., Basso & Capitani, 1985; Luria, Tsvetkova, & Futer, 1965; Tzortzis, Goldblum, Dang, Forette, & Boller, 2000). Interestingly, most of these reports of spared musical processing following left-hemisphere injury are of trained musicians. Conversely, there are case reports of patients who could not process music (acquired amusia) but were able to process speech stimuli (reviewed in Peretz & Coltheart, 2003). Other than the few mentioned earlier (Luria et al., 1965; Peretz, 1993; Slevc et al., 2016), most studies did not assess the hierarchical structure of language and music, and there have been few group studies (but see Sammler, Koelsch, & Friederici, 2011). While these cases suggest that processing of musical structure *can* be preserved following left-hemisphere injury, the lack of group studies leaves it unclear if the musical structure is *typically* spared.

It is also important to document whether musical processing is preserved following brain injury given the increased interest in music-supported rehabilitation (e.g., Francois, Grau-Sanchez, Duarte, & Rodriguez-Fornells, 2015; Särkämö et al., 2008). Another important question in the music–language relationship is whether prior musical ability is associated with a neuroprotective advantage towards language impairment in individuals with brain lesions. Both music training programs and regular leisure listening promote perceptual, emotional, and sensorimotor changes in neurological conditions such as dyslexia, spatial neglect, hemiparesis, Parkinson's Disease, and aphasia [Besson et al., 2007; Dittinger et al., 2017; Tamplin, Baker, Jones, Way, & Lee, 2013; see reviews by Särkämö (2017) and Sihvonen, Sarkamo, et al. (2017)] and, as mentioned earlier, musically trained individuals show some advantages in language processing (Brod & Opitz, 2012; Jentschke & Koelsch, 2009). However, it is still unclear if musical training (prior to stroke) is associated with better language abilities in PWA and if these effects include language syntax. In addition, it is unclear if such a relationship would require formal musical training or if advantages might also be associated with more general musical skills or behaviors (e.g., listening to music; Müllensiefen, Gingras, Musil, & Stewart, 2014). Here, we assess this general construct of *musical sophistication* with self-report questionnaires (Müllensiefen et al., 2014; Ollen, 2006).

Finally, examining syntactic processing of music and language in PWA informs the debate about the domain generality of syntactic processing and syntactic deficits. While some view syntactic processing as a language-specific mechanism (Campbell & Tyler, 2018; Fedorenko et al., 2012), others propose that syntactic processing is shared across domains (SSRIH by Blackwell & Bates, 1995; Chiang et al., 2018; Musso et al., 2015; Patel, 2003). In fact, grammatical deficits in aphasia (agrammatism) are poorly understood, particularly with reference to associated domain general structural processing (Christiansen, Louise Kelly, Shillcock, & Greenfield, 2010; Schuchard & Thompson, 2017). The present study had three goals. The first, and primary, was to better elucidate the relationship between musical and linguistic structural processing in PWA. Specifically, we asked whether processing of musical structure is impaired relative to neurotypical adults. If musical structural processing is unimpaired in PWA, then musical structural processing can be concluded to not rely on left-hemisphere peri-Sylvian language network. We assessed both an unselected group of PWA and individuals with agrammatic aphasia. If structural processing of music and language is subserved by the same left-hemisphere peri-Sylvian network, then musical processing should be particularly impaired in persons with agrammatic aphasia (cf. Patel et al., 2008; Slevc et al., 2016). However, there is no objective cut-off in language performance that serves to diagnose agrammatism. While some authors infer agrammatism as an inherent component of nonfluent aphasia, others identify specific features in narrative language production, and still others include impaired asyntactic comprehension as a feature of agrammatism. More importantly, syntactic deficits in aphasia may be on a continuum (Malyutina, Richardson, & Den Ouden, 2016; Thorne & Faroqi-Shah, 2016). Thus, we place a stronger emphasis on examining musical structure in an unselected group of PWA, with agrammatic aphasia as a secondary analysis.

The second goal was to examine the association between linguistic syntactic processing and musical syntactic processing in PWA (or in neurotypical individuals). If music and language utilize the same structural processing mechanism, then performance measures should be correlated at an individual level, while controlling for task demands. We used two types of tasks, those that involved deliberate evaluation of music/language structure and those that examined more automatic, implicit processing of music/language structure. We predicted that the implicit task performance is more likely to be associated with each other than explicit because implicit tasks capture online syntactic computations, while explicit tasks necessitate a deliberate evaluation of syntactic representations.

The third goal was to assess whether musical ability is associated with language performance in PWA. We examined the overall severity of language impairment and its relationship with musical training and musical sophistication. Such an association would inform the debate about the cognitive benefits of music (Harris, 2018).

Materials and methods

Participants

Twenty-three PWA (15 female, 8 male) and 20 neurotypical adults (13 female, 7 male) participated in this study. PWA had suffered a single left-hemisphere cerebrovascular accident (CVA) in the region of the middle cerebral artery. All but two PWA had suffered an ischemic CVA (APM18 and APM20 had a hemorrhagic CVA). Neurotypical participants

were all right-handed (Dragovic, 2004) and matched in approximate age, $M = 56.7$ years, $SD = 8.2$, range: 44–74 years, to PWA, $M = 59.8$ years, $SD = 10.1$, range: 40–81 years, $t(41) = 1.1$, $p > .05$. The groups did not differ in years of education, Healthy $M = 16.5$, $SD = 2.7$, range: 13–24; Aphasia $M = 16.7$, $SD = 4.2$, range: 13–25; $t(41) = 1.3$, $p > .05$. Neurotypical participants did not report hearing loss, speech-language difficulties, history of substance abuse, or neurological disorders. As per medical records and caregiver reports, PWA did not have significant neuropsychiatric conditions such as substance abuse, dementia, or psychiatric disturbances (except for APM2, who had a prior diagnosis of bipolar disorder). Participants were primary English speakers with at least a high school education and scored less than a 5 (out of 10 items) of the Geriatric Depression Scale (Sheikh & Yesavage, 1986). All participants also passed a hearing screening (40 dB at 500, 1 K, 2 K Hz) and vision screening (6/20 on Snellen chart) or had corrected hearing/vision. Participant details are provided in Table 1. APM2 was also described in Slevc et al. (2016).

Language, cognitive, and music background

PWA were administered the Western Aphasia Battery-Revised (WAB-R, Kertesz, 2006) to determine the subtype and severity of aphasia. Three PWA had an aphasia quotient (AQ) higher than 93.8, the general cut-off for aphasia (Kertesz, 2006) and are referred as “non-aphasic by WAB” (NA-WAB, Fromm et al., 2017). We included these participants because they continued to experience spoken language difficulties in conversation and because including participants with a broad severity range increases the chance of revealing task associations.

Narrative language samples were elicited using selected stimuli from the Aphasia bank project (www.talkbank.org/aphasiabank, MacWhinney, Fromm, Forbes, & Holland, 2011) and included a personal narrative (*Describe an important event in your life*), a procedural narrative (*How do you make a peanut-butter-and-jelly sandwich?*), picture scene descriptions (the *Broken Window* and *Cookie Theft* pictures) and re-telling of the Cinderella story. Samples were transcribed, and lexical and syntactic measures were extracted using EVAL and KIDEVAL utilities of Computerized Language Analysis (CLAN, MacWhinney, 2013). The developmental sentence score (DSS, Lee & Canter, 1971) represents syntactic complexity, and this measure is shown to be a reliable indicator of syntactic abilities in PWA (Thorne & Faroqi-Shah, 2016). Persons with agrammatic aphasia were identified based on overall aphasia profile from the WAB-R (comprehension better than spontaneous speech), agrammatic features in narrative samples (fragmented utterances and paucity of verbs and verb morphology), and low DSS scores. Based on these criteria, 12 PWA (7 female) were determined to have agrammatic aphasia. The agrammatic group was more severe, WAB-AQ Mean (SD): Agrammatic PWA = 56.8 (14.7), Non-agrammatic PWA = 90 (7.8), Mann-Whitney $U = 1$, $p = .004$, and had lower DSS scores than the non-agrammatic PWA participants, DSS Mean (SD): Agrammatic PWA = 7.8(4.6), Non-agrammatic PWA = 14.8 (4.8), Mann-Whitney $U = 1 = 16$, $p = .006$. The agrammatic group did not differ from the non-agrammatic PWA or neurotypical group in age, education, OMSI scores, and pre-morbid IQ, all Mann-Whitney U values >33 for non-agrammatic comparisons and >69 for neurotypical comparisons, all p -values $>.05$. Agrammatic PWA are identified in Table 1. The inventory of the articulation characteristics of apraxia from the Apraxia Battery for Adults-2nd Edition (Dabul, 2000) was used to determine if apraxia was present.

Table 1. Participant information.

Participant	Age(yr)	Gender	Handedness	Edu (yr)	Occupation	Pre-IQ	Lesion	TPO (yr)	WAB-AQ	Aphasia	DSS	OMSI	Music lessons (yr)
APM1	54, F, R			21	Financial Analyst	112.5	L. fronto-parietal	.3	57.7	*Broca's	3.5	102	0
APM2	63, F, R			12	Professional singer	104.2	L. frontal, subcortical	.3	33.6	*Broca's	3.8	954	0
APM4	64, F, R			12	Retired	114.8	L. fronto-parietal	13	65.7	*Broca's	3.3	103	0
APM5	67, M, R			12	Naval Officer	111.9	L. MCA	1	30.8	*Broca's	5.7	18	3
APM7	54, F, L			13	Not employed	107.9	NA	7	97	NAWAB	11.8	119	5
APM8	40, F, R			16	Retired Financial Planner	114.2	L. parietal	2	92.8	Anomic	NA	101	0
APM9	74, M, R			24	Professor	146.8	L. fronto-temporal	4	63.4	*Broca's	16.9	133	0
APM10	68, M, R			16	Retired Manager	112.2	NA	3	87.1	Anomic	8.8	36	0
APM11	46, F, R			16	Financial Analyst	111.8	NA	.1	85.1	Anomic	19.6	351	5
APM13	69, M, R			14	Administrator	117.5	L. temporal	2	87.6	Anomic	NA	49	7
APM14	57, F, L			18	Not employed	126.1	L. parietal	8	75.3	Conduction	11	20	0
APM15	54, F, R			13	Retired	106.3	L. MCA	2	50.7	*Broca's	6.7	20	0
APM17	53, F, R			16	Supervisor	109.5	L. frontal, subcortical	7	74.1	*Broca's	12.9	NA	NA
APM18	48, M, R			24	Speech Recog. Analyst	138.6	NA	4	98	NAWAB	16.5	131	2
APM19	81, M, A			15	Computer Administrator	120.8	L. inferior MCA	6	88.3	Anomic	16.2	NA	4
APM20	56, F, R			14	Architect	111.7	NA	10	99.6	NAWAB	16.8	371	0
APM22	68, F, L			15	Health Policy Analyst	136.9	L. temporo-parietal	12	92.7	Anomic	12.1	515	5
APM27	57, F, A			21	Self Employed	97.9	L. temporal	1	85.1	Anomic	49	54	0
AP87	73, M, R			20	Telecom. consultant	109.8	L. frontal, subcortical	4	53.7	*Broca's	4	18	0
AP91	46, F, R			20	Architect	120.6	L. frontal, subcortical	4	78.4	*Broca's	36	20	3
AP92	62, F, R			25	Lawyer	137.6	L. large perisylvian	10	60.2	*Broca's	2	339	0
AP96	54, M, R			17	Chief Info. Officer	111.5	LMCA	1	57.2	*Broca's	17	244	3
AP66	54, F, R			17	Realtor	102.8	L. fronto-parietal	1	61.2	*Broca's	50	53	1

A – Ambidextrous, DSS – Developmental Sentence Score (Lee & Canter, 1971), Edu – Education, L – Left, MCA – Middle cerebral artery, NA – Not available, NAWAB – Not aphasic as per WAB (Fromm et al., 2017), OMSI – Ollen's musical sophisticated index, R – Right, TPO – Time post Onset, WAB-AQ – Western Aphasia Battery Aphasia Quotient, * – Agrammatism (Kertesz, 2006).

General intelligence was estimated using a formula based on demographic data (Crawford, Millar, & Milne, 2001). This estimate of intelligence quotient (IQ) has been demonstrated to be highly correlated with full-scale IQ measures (Wechsler Adult Intelligence Scale, Wechsler, 1981). The two groups did not differ in estimated IQ, PWA Mean (SD) = 116.3 (13.1); neurotypical Mean (SD) = 105 (19.2); $t(37) = .9, p = .3$. Overall cognitive abilities of PWA were tested using selected subtests of the Cognitive Linguistic Quick Test (CLQT, Helm-Estabrooks, 2001, *Symbol cancellation, Clock drawing, and Symbol Trails*) and a memory span test which has been normed for PWA (De Renzi & Nichelli, 1975).

Musical sophistication was assessed using the overall sophistication score from the Ollen Musical Sophistication Index (OMSI; Ollen, 2006) and the number of years of music lessons (one of the questions from OMSI questionnaire) was additionally used as a more specific measure of musical training. The OMSI is a 10-item questionnaire with questions about musical training, experience, and ability. The OMSI was developed based on expert ratings as a criterion variable, so overall OMSI score indicates the (predicted) probability that a musical expert would characterize the participant as musically sophisticated (multiplied by 100, thus scores range from 0 to 1000). For example, a score of 131 (APM11) indicates a 13% probability that a music expert would categorize this person as “musically sophisticated.” Neurotypical adults and PWA did not differ in their OMSI scores, neurotypical $M = 247.3, SD = 267.8, \text{range: } 16\text{--}940$, PWA $M = 170.3, SD = 221.5, \text{range: } 18\text{--}931, t(39) = .98, p > .05$, or years of training, neurotypical $M = 2.7, SD = 3.5, \text{range: } 0\text{--}10$, PWA $M = 1.7, SD = 2.3, \text{range: } 0\text{--}7, t(39) = .31, p > .05$.

Experimental tasks

Four computer-based tasks were developed for this study. Two acceptability judgment tasks were used as explicit or off-line measures of structural sensitivity: *Sentence Judgment* and *Chord Judgment*. Two implicit or on-line measures were used: *Word Monitoring* and *Harmonic Priming*. The tasks' stimuli and procedures are summarized in Table 2. Participants were tested in a quiet room and performed the four tasks in a randomly assigned order. All participants responded with their left hand to accommodate for right hemiparesis in PWA.

Explicit processing

Sentence judgment

The Sentence Judgment task was adapted from Faroqi-Shah and Dickey (2009), in which participants judge the *goodness* of a sentence. One hundred sentences were used: 40 sentences with morphosyntactic violations, 40 accurate sentences and 20 fillers with semantic violations (e.g., *The glass frame runs upstairs*). The morphosyntactic violations included equal numbers of sentences with tense violations (e.g., *Last week the tall tourist stays at a motel*) and local syntactic violations (e.g., *The baby is spilled the milk*), and the main verb was the decision point where listeners could detect a morphosyntactic violation. The number of words per sentence was matched across conditions. The sentences were audio-recorded by a male native speaker of English.

Participants were instructed to listen to the sentences and make a quick and accurate judgment of its goodness. Experimental trials followed five practice trials and were

Table 2. Details of the experimental tasks.

Task	Stimuli	Example
Explicit processing		
Language – sentence judgment	40 inaccurate sentences (morphosyntactic violations) 20 fillers (semantic violations) 40 accurate sentences	Last week the tall tourist stays at a motel The glass frame runs upstairs The reporter will ask a question
Music – musical chord judgment [#]	36 sequences containing an out of key (unexpected) chord 36 sequences where all chords come from the same musical key	Illustrated in Figure 1
Implicit processing		
Language – word monitoring	45 inaccurate sentences (morphosyntactic violations) 30 fillers (semantic violations) 75 accurate sentences	The teacher trimmed the *students to do well in class The blue sky laughed at the *clown The girl will drink *lemonade if it isn't too sour.
Music – harmonic priming	24 “unexpected” sequences, last chord was subdominant (I-IV) 24 “expected” sequences, last chord was tonic (V-I)	Illustrated in Figure 2

[#]Stimuli were from Patel et al. (1998); *Start of response timing for word monitoring.

presented in a random sequence. Participants pressed a key to progress to the next trial. Response accuracy and false alarms were used to calculate A' (Zhang & Mueller, 2005), a measure of sensitivity to the task. A' values can range from .5 (chance performance) to 1 (perfect performance). Additionally, to directly compare our data with the findings of Patel et al. (2008), the difference between the proportion of hits and false alarms was calculated (henceforth $\Delta H-FA$); a difference score of 0 indicates guessing and a score of 1 indicates a perfect score.

Musical chord judgment

Stimuli for the musical acceptability judgment task were 36 chord sequences from Patel et al. (1998), consisting of three sequences in each of the 12 major musical keys. Chord sequences were played in a piano timbre, ranged from 7 to 12 chords in length, and established a clear musical key. Each sequence occurred in both an “acceptable” form, with all harmonically expected (in-key) chords, and an “unacceptable” form, where one chord (the fifth or later) was replaced with another from a harmonically distant key (see Patel et al., 1998, for details). The conditions are illustrated in [Figure 1](#). Items were presented in a fixed pseudorandom order, constrained such that the acceptable and unacceptable versions of each sequence occurred in different halves of the task and at least six trials apart. Experimental trials followed two practice trials.

Participants were instructed to listen to each sequence and to respond by pressing one of the two keys depending on whether the tones fit together or not. After four practice trials with feedback (in-key and out-of-key versions of two items), participants judged the remaining 68 sequences (pressing any key to start each new trial), with a break halfway through. As for the sentence judgment task, both A' (Zhang & Mueller, 2005) and $\Delta H-FA$ (cf. Patel et al., 2008) were calculated as measures of task performance.

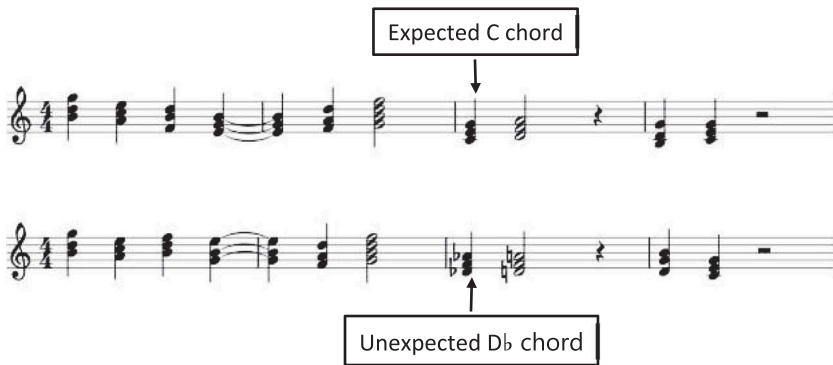


Figure 1. Example notation for one item in the musical chord judgment task. The example chord sequence is in C major. In the expected chord sequence (top), all chords come from the C-major scale, whereas in the unexpected chord sequence (bottom), one chord comes from a distantly related key (here, a D-flat major chord, indicated by an arrow).

Implicit processing

Both implicit processing tasks relied on response time (RT) difference scores. RTs were calculated as the time between the onset of the target (word or chord) and the participant's response, and were treated in the same way for each task: trials in which participants failed to respond (no responses), responded earlier than 100 ms, later than 10,000 ms, or more than two standard deviations from their mean RT were eliminated. In addition, because the overall slowness of PWA could potentially result in larger difference scores than neurotypical adults, the neurotypical group's effects (mean and standard deviations) were used to calculate standardized scores (Z-scores) for each task for each PWA. These Z-scores indicate the number of standard deviations by which a PWA's score differs from the neurotypical group.

Word monitoring

The word monitoring task was modeled after Peelle, Cooke, Moore, Vesely, and Grossman (2007) and consisted of 150 sentences: 75 correct sentences and 75 incorrect sentences. Incorrect sentences included 30 filler sentences with semantic anomalies (e.g., *The blue sky laughed at the clown*) and 45 critical sentences with morphosyntactic violations (equal numbers of tense, thematic and word class violations). In these sentences, the target word to be monitored (indicated by * in the following examples) occurred shortly after a grammatical violation. Following Friederici (1995) and Peelle et al. (2007), in sentences with *thematic violations*, the verb's arguments violated selectional restrictions which constrain the verb's meaning (e.g., *The teacher trimmed the *students to do well in class*), *morphosyntactic violations* consisted of errors with functional morphology (e.g., *The woman will removing her *shoes in the front porch*), and in *word class substitutions*, a noun replaced the main verb (*The driver will folder the *roses to the new office*). In fillers and correct sentences, the word to be monitored occurred at different positions to preclude participants from predicting word location. Stimuli were recorded by a female native speaker of English and the timing of the word to be monitored was extracted from the audio files.

Participants were instructed to monitor spoken sentences for a specific target word and press the spacebar as quickly as possible when that word occurred. When target words follow grammatical errors, participants are typically slower to respond. This slowing is taken as evidence for sensitivity to that grammatical error (Peelle et al., 2007). Each trial began with the auditory presentation of the target word, followed by a beep and the sentence 1000 ms later. The next trial started 1500 ms after participant response. Stimuli were presented in a pre-determined random sequence, following five practice trials. The critical measure was the *word monitoring effect*, which is the mean reaction time difference between sentences with morphosyntactic violations and correct sentences.

Harmonic priming

This paradigm is sensitive to online processing of musical structure (Bharucha & Stoeckig, 1987; Tillmann, Bigand, Escoffier, & Lalitte, 2006), where participants' judgments about a non-harmonic feature of a target chord (the chord's timbre) are influenced by that chord's harmonic function. The stimuli were 24 eight-chord sequences: the first seven chords were played with a harpsichord timbre and the final chord was played either with a trumpet or a vocal (choir) timbre (Figure 2). The sequences ended either with an authentic cadence, where the last chord was a highly expected tonic (V-I), or a less-expected subdominant chord (I-IV). Sequences were created such that the same final two chords occurred in each tonal context, thus the comparison of harmonic conditions involved acoustically identical chords. Participants were instructed to listen to each sequence and quickly press one of the two keys depending on whether the final chord was played by a trumpet or sung by a choir. Line drawings of a trumpet and of a choir appeared on the screen over the appropriate keys.

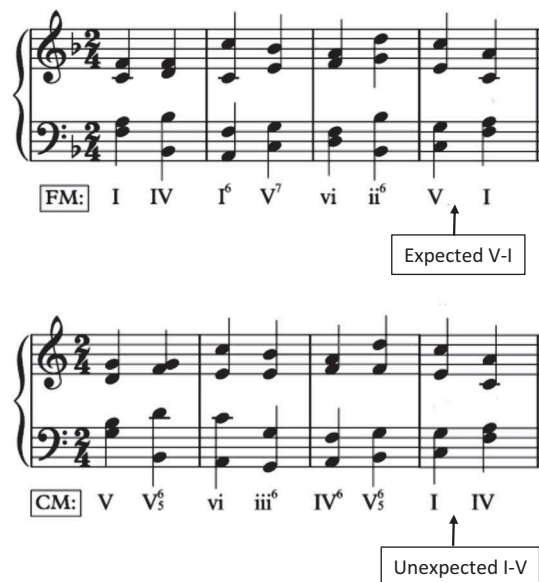


Figure 2 displays two musical staves illustrating example stimuli from the Harmonic Priming task. The top staff is in F Major (FM) and the bottom staff is in C Major (CM). Both staves show an 8-chord sequence. The top staff sequence is I, IV, I⁶, V⁷, vi, ii⁶, V, I. The bottom staff sequence is V, V⁶, vi, iii⁶, IV⁶, V⁶, I, IV. Arrows point to the final chords: 'Expected V-I' for the top staff and 'Unexpected I-V' for the bottom staff.

Figure 2. Notations of example stimuli from the Harmonic Priming task. In each 8-chord sequence, the first seven chords were harpsichord timbre and the last chord was a trumpet or choir. The expected condition ended on a tonic chord in an authentic cadence (V-I) and the unexpected condition ended on a subdominant chord in an I-IV sequence.

at the onset of the final chord. After examples of the two timbres and two practice trials (one ending with each timbre), participants heard and categorized 48 sequences with a short break halfway through. Items were presented in a fixed pseudorandom order such that the trumpet- and choir-endings of each sequence occurred in different halves of the task and at least five trials apart. A new trial started 1500 ms after a participant's response for the previous trial. The critical measure was the *harmonic priming effect*, which is the difference in mean reaction times for subdominant (I-IV) versus expected (V-I) chord sequences.

Results

Explicit processing

The two measures of interest were A' and ΔH -FA for language and musical processing (see Table 3 and Figure 3). PWA demonstrated significantly reduced sensitivity in detecting anomalous sentences compared to the neurotypical group, as measured by A' , $t(24.2) = 5.3$, $p = 0.000$ and ΔH -FA values, $t(31.5) = 6.8$, $p = 0.000$, equal variances not assumed. PWA also

Table 3. Performance of neurotypical and aphasic groups on the experimental tasks.

Task	Critical measure	Neurotypical mean (SD)	PWA mean (SD)	Agrammatic mean (SD)
Explicit processing				
Language – sentence judgment	A-prime	0.95 (0.04)	0.74 (0.2)***	.68 (.2)**
	Prop. Hits vs False Alarms (ΔH -FA)	0.82 (0.1)	0.4 (0.2)***	.3 (.2)**
Music – musical chord judgment	A-prime	.74 (0.13)	.65 (0.2)	.64 (.2)
	Prop. Hits vs False Alarms (ΔH -FA)	0.3 (0.2)	.2 (.2)	.2 (.3)
Implicit processing				
Language – word monitoring	Word monitoring effect (ms)	99.1 (33.5)	90.8 (76.7)	50.4 (87.4)
	Word monitoring effect Z score	-.15 (1.2)	-.24 (2.2)	-1.4 (2.6)
Music – harmonic priming	Harmonic Priming Effect (ms)	-45.8 (44)	-56.1 (158.2)	-7.8 (96.9)
	Harmonic Priming Effect Z score	.05 (.99)	-.13 (3.4)	.9 (2)

Significant differences between neurotypical and aphasic groups are indicated (** $p < .01$, *** $p < .001$).

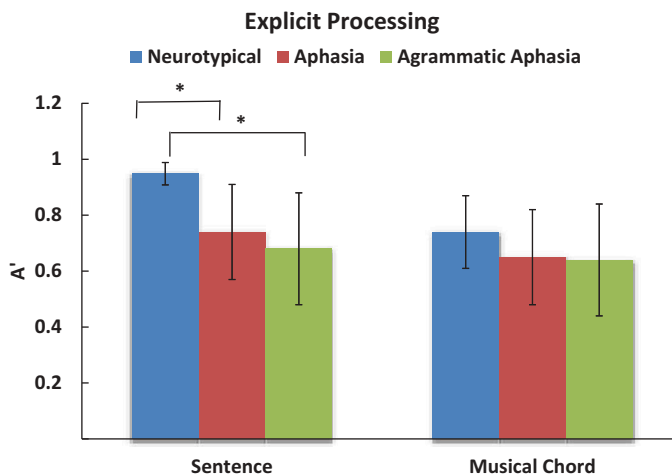


Figure 3. Performance on the explicit judgment tasks. See text for details on A' calculation. Error bars indicated standard deviation, * $p < .001$.

showed numerically poorer sensitivity to detection of musical anomalies compared to the neurotypical group, but these comparisons were not statistically significant, A' values: $t(38.3) = 1.8, p = .08$, see [Figure 3](#); ΔH -FA values: $t(40.9) = 1.6, p = .09$; equal variances not assumed. In sum, PWA showed deficits in explicit processing of sentences, while musical processing was relatively comparable to neurotypical adults.

To test the possibility that only PWA with syntactic deficits might show an impairment in musical processing (Patel et al., 2008) which could be masked in the full group, we compared performance of 12 agrammatic PWA with neurotypical adults ([Figure 3](#)). As in the whole group comparisons, agrammatic PWA performed worse (lower A' values) than neurotypical adults for Sentence Judgments, Mann-Whitney U test, U value = 6.5, $p = .0001$, but not for Musical Chord Judgments, Mann-Whitney U test, U value = 89.5, $p = .2$. There were also no significant differences in A' scores between agrammatic PWA and non-agrammatic PWA either task, Mann-Whitney U test, both U values >60, both p values > .1.

Neurotypical adults and PWA performed more slowly and less accurately for Musical Chord Judgments compared to Sentence Judgments, Mean (SD) of music vs. language for the neurotypical group: $A' = .7 (.12)$ vs. $.9 (.04)$; Mean RT = 6831 (584) vs. 1755 (422) milliseconds; music vs. language for the PWA group: $A' = .6 (.12)$ vs. $.7 (.2)$; Mean RT = 7234.8 (624) vs. 2429.2 (849) milliseconds, indicating that making judgements about musical sequences was generally more challenging than language processing. This is also evident in the smaller ΔH -FA values for musical judgments ([Table 3](#)).

Implicit processing

Both PWA and Neurotypical participants successfully monitored for the word or timbre on more than 80% of the trials. However, PWA successfully monitored for fewer trials than Neurotypical adults, Word monitoring Mean (SD): PWA = $.80(.20)$, Neurotypical = $.93(.10)$, $t(23.7) = 3.2, p = .000$; Harmonic Priming Mean (SD): PWA = $.80(.20)$, Neurotypical = $.99(.01)$, $t(20.2) = 3.7, p = .007$, equal variances not assumed. PWA had significantly longer RTs than the neurotypical group for both experimental tasks, both $t(38) > 15$, both p -values < .01, supporting the use of standardized scores for between-group statistical comparisons. The critical measures were the RT differences between anomalous and expected trials: the word monitoring effect and harmonic priming effect ([Table 3](#)). Positive word monitoring effects indicate that both groups took longer to monitor for target word for sentences with morphosyntactic violations. Negative harmonic priming effects in [Table 3](#) indicate longer RTs for the concordant (V-I) than the discordant (I-IV) sequence. These results are illustrated in [Figure 4](#).

These negative harmonic priming effects are surprising as they are opposite the pattern that is typically found; namely tonic facilitation (e.g., Bharucha & Stoeckig, 1986; Tillmann, Janata, Birk, & Bharucha, 2003; Tillmann, Bigand, et al., 2006; among others). Slevc et al. (2016) also reported this 'reverse' pattern and suggested that the faster (rather than slower) responses to the final subdominant compared to tonic in this task likely reflect two aspects of this particular task and set of stimuli. First, in contrast to most harmonic priming/timbre judgment tasks that contrast final chords of *same vs different* timbres, the target chord here was always of a different timbre than the previous context (a change made in order to make the task simpler for PWA). However, priming effects are typically

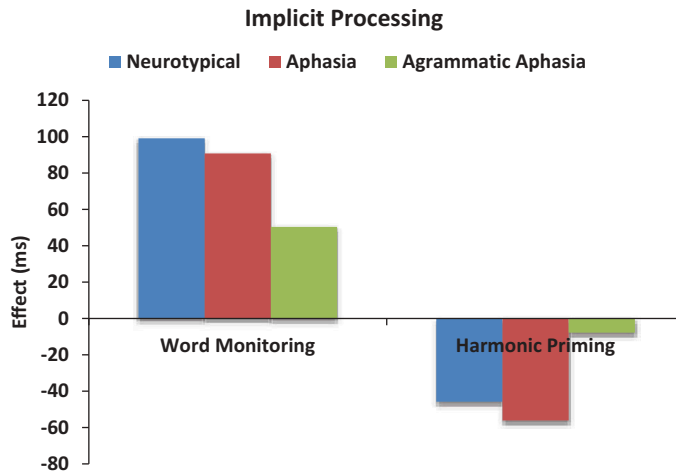


Figure 4. Performance on the implicit judgment tasks. See text for details on calculation of word monitoring and harmonic priming effects. Standard deviation is given in Table 3.

strongest for “same” responses and smaller (sometimes even reversed) for “different” responses (e.g., Marmel & Tillman, 2009), which fits with the pattern found here. Second, the “unexpected” subdominant chord in these stimuli always followed an authentic cadence (i.e., last three chords in the subdominant condition were V-I-IV). Thus, in the subdominant condition, participants heard a nicely completed harpsichord cadence followed by a new chord from a trumpet or choir. In contrast, in the tonic condition, participants heard an incomplete harpsichord sequence that was (perhaps surprisingly) completed in a trumpet or choir timbre. In any case, while this “reverse” effect was unexpected, it nevertheless indicates sensitivity to harmonic structure because the target chords were identical except for their harmonic function.

Importantly for the questions asked here, the size of the standardized word monitoring effect did not differ significantly between the PWA and Neurotypical groups, $t(25.2) = .15$, $p = .8$ nor did the size of the standardized harmonic priming effects, $t(23.6) = .2$, $p = .8$, equal variances not assumed (Table 3). The subgroup of agrammatic PWA also did not differ significantly from Neurotypical adults on either task, Word monitoring Mann-Whitney $U = 59$, $p = .4$; Harmonic Priming Mann-Whitney $U = 145$, $p = .2$, or from Non-agrammatic PWA, Word monitoring Mann-Whitney $U = 21$, $p = .1$; Harmonic Priming Mann-Whitney $U = 34$, $p = .2$. The PWA group thus showed normal implicit sensitivity to linguistic and musical structure.

Association between tasks

The correlations between musical and language measures for both groups are given in Table 4. Given the number of comparisons, $p < .01$ was adopted as the threshold of significance to minimize Type I Error.

Table 4. Correlations between music and language measures.

	Sentence judgment	Musical chord judgment	Word monitoring	Harmonic priming
	A' Prime	A' Prime	WM effect Z	HP Effect Z
<i>Sentence judgment A'</i>				
Neurotypical		.14	.24	.17
PWA		-.20 (.26)	.45 (.9*)	-.32 (-.20)
<i>Musical chord judgment A'</i>				
Neurotypical			-.05	-.36
PWA			.16 (-.01)	-.13
<i>Word monitoring effect Z</i>				
Neurotypical				.07
PWA				-.43 (-.05)
<i>OMSI</i>				
Neurotypical	.37	.40	-.14	-.30
PWA	.18 (-.40)	-.01 (.10)	-.77* (-.90*)	.05 (-.10)
<i>Years (Lessons)</i>				
Neurotypical	-.40	.13	.12	-.17
PWA	.21(.20)	.2(.48)	.38(.43)	-.60*(-.50)

Significant comparisons are indicated (* $p < .01$, $\sim p < .05$). The numbers in parentheses are correlations (Spearman r_s) of the agrammatic PWA subgroup.

Relationship between musical and linguistic syntactic processing

Separate within-group correlations were computed for the explicit and implicit tasks (see Table 4). For neurotypical adults, the full PWA group, and the agrammatic PWA subgroup, there were no significant correlations between performance on the language and music syntax tests for either explicit or implicit paradigms, all Pearson $r < (\pm).45$, $p > .01$; for agrammatic PWA: all Spearman $\rho_s < (\pm).45$, $p > .01$.

Relationship between musical ability and task performance

In the neurotypical group, there were no significant correlations between higher OMSI/more years of lessons and music or linguistic syntactic task performance, all Pearson $r < (\pm).40$, $p > .01$ (Table 4). In PWA, explicit processing tasks also did not show any significant association between musical ability and task performance. However, for implicit tasks, PWA's musical sophistication correlated with linguistic syntactic processing, OMSI and Word monitoring effect Z-score: $r = -.77$, $p = .001$ and this correlation was stronger for agrammatic PWA, $r_s = -.90$, $p = .001$ than for non-agrammatic PWA, $r_s = -.60$, $p = .08$. PWA's musical training also correlated with implicit musical syntactic processing, PWA's Years lessons and Harmonic Priming effect Z-score: $r = -.66$, $p = .003$; agrammatic PWA $r_s = -.52$, $p = .15$; non-agrammatic $r_s = -.6$, $p = .06$. These negative correlations indicate that higher OMSI/more years of lessons was associated with a smaller deviation (z-score) from the neurotypical group's performance.

Relationships between musical ability and language deficit in aphasia

The number of years of training correlated positively with overall aphasia severity (that is, with higher WAB-R AQ, $r = .47$, $p = .03$) but this was marginally significant. The agrammatic PWA subgroup did not show any significant association between years of music lessons and WAB-R AQ, $r_s = .31$, $p = .4$.

Interim discussion of musical ability and language deficit in aphasia

There was no association between musical and linguistic syntactic performance in PWA. There was, however, an association between overall OMSI score and implicit linguistic syntactic processing. Years of music lessons showed a weak association with aphasia severity, although OMSI scores were not correlated with language impairment. Given the inconsistent pattern of associations between musical abilities and language performance in PWA, it was important to further verify this relationship. It is possible that these significant associations occurred by chance or that our study measures or the number/characteristics of participants may have limited our analysis. Therefore, we tested the replicability of these findings in a new group of PWA, after addressing three issues with the music and language measures used with the original sample.

One limitation is the OMSI, which was developed and validated only on participants who were engaged in a variety of music-related activities (Ollen, 2006), and may not apply to a more general population like the participants in this study. The OMSI has also been criticized for focusing on specific activities such as duration of musical training and the ability to play an instrument (Levitin, 2012). In the replication study, the Goldsmith's Musical Sophistication Index (Gold-MSI; Müllensiefen et al., 2014) was used because it adopts a broader view of musicality and includes self-report questions on musical understanding, appreciation, evaluation, and communication (e.g., *I don't spend much of my disposable income on music; I can tell when people sing or play out of tune with the beat*). (Note, however, that the OMSI was also administered for comparison.). The Gold-MSI also includes more conventional rating items such as playing an instrument, improvisation and having a good sense of pitch and rhythm, and was normed on over 100,000 participants from the general population (Müllensiefen et al., 2014).

A second limitation of the current study is that the association between language impairment and music could be mediated by a third variable, such as socioeconomic status or general cognition (Črnčec, Wilson, & Prior, 2006; Harris, 2018; LaCroix et al., 2015; Okada & Slevc, 2018; Schellenberg, 2011). It has been argued that individuals with higher IQ are more likely than their lower-IQ counterparts to take music lessons (Schellenberg, 2011). Given that musical sophistication could co-occur with other lifestyle factors that could enhance cognitive reserve (i.e., how some people cope better with brain pathology than others; Stern, 2009), we added a self-report measure of cognitive reserve (the Cognitive Reserve Index Questionnaire [CRIq]; Nucci, Mapelli, & Mondini, 2012) to tease out possible associations between musical ability and engagement in cognitive activities.

A third limitation is that the aphasia quotient of the Western Aphasia Battery-Revised (Kertesz, 2006) is a language composite score derived from multiple sub-tests (spontaneous speech, auditory comprehension, repetition, and naming). If musical abilities are associated with a specific aspect of language (such as auditory comprehension), then this association may not be accounted for. Therefore, in this replication study, in addition to WAB-R AQ, we examined the association between music and auditory verbal comprehension, given prior evidence of enhanced auditory processing in musicians (Forgeard, Winner, Norton, & Schlaug, 2008). Furthermore, items in each sub-test in the WAB-R are weighted differently for scoring. For instance, each naming response receives 3 points while auditory comprehension items receive 1 point each. We calculated the total proportion of errors to address the differential weighting (Gonzalez-Fernandez et al., 2011).

Association between musical ability and language impairment – further data

Participants

Fifteen new PWA (9 females, 6 males) were recruited for the study. Like the first group, all participants developed aphasia following a left-hemisphere CVA and were native English speakers, who did not learn a second language before the age of 12 years. Participants had at least a high school education, no uncorrected visual or hearing deficits, and no history of psychiatric conditions. If a participant had more than mild apraxia of speech (Diadochokinetic Rate subtest score <7 , *Apraxia Battery for Adults-Second Edition*, ABA-2; Dabul, 2000), language measures involving verbal expression (e.g. naming) were excluded from the analyses. Participant details are provided in Table 5. Participants did not differ from the original group of 23 participants in age, mean (SD) = 62.2 (12.6) vs. 59.2 (10.1) years, $t(36) = .8$, $p = .4$, education, mean (SD) = 16.5 (2.6) vs. 16.8 (4.1) years, $t(36) = .3$, $p = .7$, time post-onset of aphasia, mean (SD) = 5 (2.5) vs. 4.5 (3.9) years, $t(36) = .4$, $p = .6$, language severity per WAB-R AQ, mean (SD) = 70.7 (21.5) vs. 72.8 (19.9), $t(36) = .3$, $p = .7$, OMSI scores, mean (SD) = 119.5 (98.9) vs. 170.3 (221), $t(34) = .4$, $p = .4$, or years of music lessons, mean (SD) = 1 (1.6) vs. 1.6 (2.3), $t(36) = .8$, $p = .4$.

Music and language measures

Musical sophistication in this sample was again measured using the OMSI (Ollen, 2006) and number of years engaged in music lessons, for comparison with the previous experiment, and also with the Goldsmiths Musical Sophistication Index (Gold-MSI, version 1.0; Müllensiefen et al., 2014). The Gold-MSI includes 39 items that are self-rated on a 7-point scale in five categories: Active Engagement, Perceptual Abilities, Musical Training, Singing Abilities, and Emotions. Self-ratings on these five categories are used to derive an overall standardized score for musical sophistication. Overall cognitive engagement was determined by the CRIq (Nucci et al., 2012), with self-report questions covering three sub-areas that are commonly used

Table 5. Participant details for the follow-up study.

Participant	Age(yr), Gender, Handedness	Edu (yr)	Occupation	Pre-IQ	TPO (yr)	WAB-AQ	Aphasia
AP119	66, F, R	12	Technician	104.8	2	73.6	Anomic
AP117	68, F, R	17	Homemaker	103.6	7	96.9	NAWAB
AP118	81, M, R	23	Orthopedic surgeon	137.5	2	47.9	*Broca's
AP114	41, M, R	19	Telecomm. engineer	123.1	6	60.7	*Broca's
AP81	74, M, R	18	Chief Exec. officer	127.3	9	90.8	Anomic
AP88	52, F, L	15	Secretary	107.6	10	80.5	Conduction
AP82	58, F, R	14	Food demonstrator	101.7	8	93.7	Anomic
AP107	56, F, R	16	Graphic designer	115.3	7	93.9	NAWAB
AP83	57, M, R	15	Shipping clerk	103.3	5	62.8	*Broca's
AP111	49, F, R	15	Sales manager	107.0	4	69.5	*Transcor. Motor
AP113	87, F, R	16	Nurse	120.9	2	33.3	Wernicke's
AP95	58, M, R	19	Chief Oper. Off.	121.0	4	34.7	*Broca's
AP115	49, F, R	14	Child care	100.0	2	57.8	*Broca's
AP93	67, M, R	18	Contract mediator	115.6	5	67.4	Conduction
AP120	70, F, R	17	Accountant	124.8	2	97	NAWAB

Edu Education, L – Left, NAWAB – Not aphasic as per WAB (Fromm et al., 2017), R – Right, TPO – Time post Onset, WAB-AQ – Western Aphasia Battery Aphasia Quotient (Kertesz, 2006), * – Agrammatic PWA.

Table 6. Correlations between measures of musical ability and language performance in persons with aphasia (* = $p < .01$, ~ = $p < .05$).

	OMSI	Years lessons	Gold-MSI	CRIq
<i>Original group (N = 23)</i>				
WAB-AQ	-.20	.47~	-	-
<i>Follow-up group (N = 15)</i>				
WAB-R AQ	-.20	.43	.40	-.02
WAB-R %Errors	-.14	-.43	-.40	.20
WAB-R Aud. Compr.	.04	-.35	-.41	.07
<i>Combined (N = 38)</i>				
WAB-AQ	-.20	.45*		

proxies for cognitive reserve: Education, Working Activity, and Leisure Time. There are only two items related to music on the questionnaire: “Artistic activities (music, singing, performance, painting, writing, etc.)” and attending “exhibitions, concerts, conferences,” so the CRIq was considered to have little overlap with the Gold-MSI. For all questionnaires, participants were asked to respond based on their experiences prior to their stroke. Language measures were WAB-AQ, proportion of errors (excluding spontaneous speech and animal fluency tasks), and auditory comprehension subtest score.

Results

Musical sophistication and overall cognitive engagement were not correlated (Gold-MSI and CRIq, $r = 0.25$). Associations between music and language variables for the original group of PWA and the follow-up group are listed in Table 6, but none were statistically significant, $p < .01$. It is noteworthy that the correlation values between OMSI, years of lessons and WAB-R AQ were numerically similar to the original group. When both groups were combined ($N = 38$), years of music lessons correlated strongly with WAB-AQ, $r = .45$, $p = .008$. The positive correlation indicates that better language performance (higher WAB-R AQ) was associated with more (pre-stroke) years of music lessons.

We also ran three simple linear regression analyses with each language measure (WAB-R AQ, WAB-R %errors, WAB-R Auditory Comprehension) as the dependent variable and the musical measures (OMSI, Gold-MSI, Years Lessons) as predictors, with cognitive engagement (CRIq) as a covariate. None of the models were significant, all R^2 values $< .2$, all F values < 1.8 , and all p values $> .01$.

Discussion

This study investigated musical ability and its relationship with language abilities in individuals with post-stroke aphasia. The three specific questions were: whether structural musical processing is impaired in PWA, whether there is an association between musical and linguistic structural processing, and whether there is an association between prior musical abilities and language impairment in PWA. This study found that PWA’s processing of musical structure was unimpaired relative to neurotypicals. The only experimental task in which PWA showed a significant deficit was explicit sentence judgment. Second, there was no association between structural processing of music and language in either group. Third, musical ability correlated with implicit structural processing of music and

language in PWA, and musical training had a modest correlation with aphasia severity in PWA, which was evident with a larger group of 38 PWA.

Structural processing of music in PWA

PWA did not differ from neurotypical adults in the implicit and explicit structural processing of music. This was also the case for the subgroup of individuals with agrammatic aphasia, who would have been the most likely to experience a musical structural impairment if musical and linguistic structures draw on shared neural resources. The findings reported here are thus consistent with several other studies that found PWA to have spared performance on a wider range of (not-specifically-structural) musical abilities and tasks (e.g., Basso & Capitani, 1985; Kasdan & Kiran, 2018; Patel et al., 2008; Sarkamo et al., 2009; Schuppert, Munte, Wieringa, & Altenmuller, 2000; Sihvonen, Ripolles, et al., 2017; Slevc et al., 2016; Tzortzis et al., 2000; also work reviewed in Peretz & Coltheart, 2003).

Our findings are inconsistent with the only other group study to examine musical structure in PWA using both explicit and implicit tasks like ours (Patel et al., 2008). Patel et al. tested 12 Dutch-speaking individuals with Broca's aphasia and asyntactic comprehension, whereas the current study had 12 agrammatic and 11 non-agrammatic English-speaking PWA. There are also some methodological differences between the two studies, including the use of a verbal (Patel et al.) versus a keyboard (current study) response mode and somewhat different harmonic priming tasks. Note also that Patel et al. did not report a direct neurotypical versus PWA comparison for the implicit task (p.787), thus it is not clear if their data actually differ from our results. The direction of harmonic priming effect also differed across these studies (positive in Patel et al. and negative in the current study; see above for discussion) and participants' chord judgment performance was better in Patel et al. (H-FA of .5. versus .3 in the current study). In both studies, the neurotypical groups performed poorly on this task, which stands in stark contrast with their strong performance on the sentence judgment task (.8 in Patel et al. [Figure 1] and in the current study). This indicates that judgment of musical structure is challenging even for neurotypical adults, and PWA's performance needs to be interpreted with this in mind. In fact, Patel et al. (2008) noted that "the musical deficits ... were relatively mild ..." (p.788).

There are several implications of the finding of unimpaired processing of musical structure in PWA. First, we can conclude that left peri-Sylvian lesions do not play a major role in the processing of musical expectancies, at least in the PWA tested in the current study. This conclusion does not pertain to non-aphasic individuals with left peri-Sylvian (Sammler et al., 2011) or extra-Sylvian lesions. Studies that reported impaired musical processing in non-aphasic individuals with extra-Sylvian left-hemisphere lesions (Ayotte, Peretz, Rousseau, Bard, & Bojanowski, 2000; Sarkamo et al., 2009; Schuppert et al., 2000; Sihvonen, Ripolles, et al., 2017) did not specifically examine musical structure. Importantly, in these studies, left-hemisphere music agnosias were consistently less severe and more transient compared to impairments following right hemisphere lesions (but see Prior, Kinsella, & Giese, 1990). Thus, the second implication of the current results is that there are hemispheric differences in processing of language and music structure: left-hemisphere lesions significantly impair language structural processing but only have a minor (if any) impact on processing of musical structure, inconsistent with the view that syntax in music and language share left-hemisphere resources (Patel, 2003). Rather, it supports separate domain-specific representations and

processes (Peretz & Coltheart, 2003), fitting with a meta-analysis finding distinct bilateral cortical networks for music and speech processing in neurotypicals (LaCroix et al., 2015).

Associations between structural processing of music and language

We tested the logic that, if music and language utilize the same structural processing mechanism, then music and language performance measures would be correlated within individuals. We predicted that the implicit tasks were more likely to be correlated with each other than the explicit tasks. However, neither neurotypical adults nor PWA showed any correlation between music and language in either type of task. Our findings are consistent with the only other study to use this cross-task correlational approach with comparable music and language tasks (Patel et al., 2008).

It is possible that our assumption that music and language responses would be quantitatively similar and correlated was overly simplistic. Syntactic rules of language are well defined and fairly consistent across native speakers of a language. Consequently, native speakers show automatic sensitivity to syntactic structure, as demonstrated by the neurophysiological response called early left anterior negativity, ELAN (Friederici, Pfeifer, & Hahne, 1993). Structural progressions of music, however, are not characterized by such rigid expectations, and out-of-key chords in a harmonic progression can vary in their degree of irregularity. Moreover, listeners' neurophysiological responses to musical unexpectancies are variable: the apparent music-equivalent of the ELAN, the early right anterior negativity (ERAN), has a larger magnitude in musicians (Jentschke, Koelsch, & Friederici, 2005) and diminishes with repeated exposure (Koelsch & Jentschke, 2008). Coupled with laterality differences in syntactic processing (ELAN vs ERAN), the prediction of a correlation in magnitude of behavioral responses to music and language was not borne out. Additionally, PWA were significantly impaired in sentence judgments but not in chord judgments, reducing the possibility of a correlation.

In addition, it is possible that the experimental tasks may not have engaged the complex cognitive processes that are likely to reveal overlap between music and language (Slevc & Okada, 2015). The sentence unexpectancies used in this study are less complex and less ambiguous than those used in prior studies (e.g., Slevc et al., 2009; Van de Cavey & Hartsuiker, 2016). Much of the prior evidence for shared structural processing of music and language has come from relatively demanding paradigms such as task interference with simultaneous presentation of music and language (e.g., Fedorenko et al., 2009; Hoch et al., 2011; Koelsch, Gunter, et al., 2005; Kunert et al., 2015; Slevc et al., 2009). Perhaps the tasks used here were too simple to require whatever resources might be shared.

This fits with arguments that *structural* processes in music and language are, in fact, not shared. Instead, any overlap in music and language may reflect shared reliance on processes not specific to syntax. For example, overlap might only occur for tasks that require reconfiguration of an initial interpretation and draw on cognitive resources that have little to do with syntax directly (Kunert, Willems, & Hagoort, 2016; LaCroix et al., 2015; Slevc & Okada, 2015). In addition to our findings of preserved musical processing in PWA and absent correlation between music and language (see also Patel et al., 2008), this conclusion fits with evidence that interference effects between music and language are not syntax specific (Perruchet & Poulin-Charronnat, 2013; Slevc & Okada, 2015). This conclusion also is supported by laterality differences in neural responses to music and language (Friederici

et al., 1993; Jentschke et al., 2005; LaCroix et al., 2015; although note that music syntactic processing is typically associated with largely bilateral activation; e.g., Fedorenko et al., 2012; Musso et al., 2015). Finally, this conclusion fits with other neuropsychological dissociations between amusia and aphasia (Omigie & Samson, 2014; Peretz & Coltheart, 2003), even though most previous neuropsychological work has not assessed structural processing (but see Peretz, 1993; Slevc et al., 2016). This interpretation is consistent with Peretz and Coltheart's (Peretz & Coltheart, 2003) modular architecture for music and speech/language processing, and with the idea that music and language overlap only when complex, resource limiting demands occur (Loui, Grent-'t-Jong, Torpey, & Woldorff, 2005; Slevc & Okada, 2015).

Our findings also provide insight into syntactic impairments in aphasia. Participants with agrammatic aphasia showed limited syntactic structure in their narrative discourse (Section 2.2) compared to non-agrammatic PWA. Nevertheless, comprehension performance did not differ in explicit or implicit language tasks. This shows that agrammatic language production is a unique symptom, while syntactic comprehension difficulties are more pervasive in aphasia (consistent with Caplan, Waters, & Hildebrandt, 1997; Caramazza, Berndt, Basili, & Koller, 1981). PWA groups' implicit syntax processing (word monitoring task) also did not differ from that of neurotypical adults (Table 3), fitting with studies showing preserved implicit processing in aphasia (Chenery, Ingram, & Murdoch, 1990; Dickey & Thompson, 2009; Prather, Zurif, Love, & Brownell, 1997). This suggests that language representations and their automatic activation may not be significantly impaired in aphasia; instead, impairments affect the ability to operate on these activations in a timely manner, for syntactic (Dickey & Thompson, 2009) and lexical-semantic processing (Chenery et al., 1990; Prather et al., 1997).

Association between musical experience and language abilities in PWA

Musical training has been associated with better performance in speech and language tasks in neurotypical individuals (Besson et al., 2007; Brod & Opitz, 2012; Dittinger et al., 2017; Jentschke & Koelsch, 2009; Miendlarzewska & Trost, 2013; Moreno et al., 2009; Wong et al., 2007). There is also some evidence that individuals with brain injury show better language and cognitive performance if they have been musically trained, particularly if their brain injury resulted from neurosurgery and not stroke (reviewed by Omigie & Samson, 2014). However, to our knowledge, this is the first study to report an association between musical training and language impairment in post-stroke aphasia. While these results are promising, they need to be interpreted with caution. For one, the association was modest and warrants further replication. Still, this modest effect is consistent with meta-analyses of the effects of musical training on intelligence and educational achievement in children (Sala & Gobet, 2017), and on cognitive abilities in individuals with brain injury (Omigie & Samson, 2014; Sihvonen, Sarkamo, et al., 2017). Furthermore, in PWA, the modest association between musical training and language impairment in PWA is not surprising given that the primary determinant of language deficit is the structural and metabolic integrity of left perisylvian regions (e.g., Damasio & Geschwind, 1984). Thus, factors other than the lesion are likely to have a small effect on aphasia severity.

Another reason to treat these results with caution is that, while our participants' aphasia severity covered a wide range (from severe to mild: WAB-R AQ range: 30.8 to

100, mean = 71.9, median = 73.8), the extent of musical training was quite limited (years of music lessons range: 0–7, mean = 1.4, median = 0; OMSI range: 18–931, mean = 149.1, median 78). And, of course, the effects of lifestyle factors such as music are far more complex than a simple correlation, particularly given that individuals may engage in multiple potentially beneficial activities that enhance cognitive reserve (Hanna-Pladdy & Choi, 2010). Further, effects of lifestyle factors need to be delineated from the effects of intelligence and aptitude given that highly intelligent individuals are more likely to pursue activities such as music (Schellenberg, 2011). The Gold-MSI (Müllensiefen et al., 2014) and OMSI (Ollen, 2006) questionnaires had a broad set of questions that captured proxies for musical aptitude. However, these measures did not show any correlation with language severity (WAB-R AQ). It is also important to note that language severity did not correlate with cognitive reserve, as measured by CRIQ (Nucci et al., 2012). The significant findings were restricted to years of music lessons and were not found for general musical aptitude and cognitive engagement. Nevertheless, if this association can be replicated in future research, then it has important implications for the potential protective effect of musical expertise on stroke outcomes.

Conclusions

Persons with aphasia did not differ from neurotypical adults in explicit and implicit structural processing of music. This is in contrast with their severe impairment in explicitly judging language structure. These results are best accommodated by assuming the existence of domain-specific neural processes for structural processing in music and language (LaCroix et al., 2015; Peretz & Coltheart, 2003), and a left-hemisphere prominence for structural processing of language relative to music (Fedorenko et al., 2012). While there was no association between *structural* processing of music and language in neurotypical and aphasic persons, there was a *general* association between music and language in PWA such that greater musical training was associated with better performance on music and language tasks. This adds suggestive evidence to the literature on long-term neuroplastic effects of musical training. Future research should examine musical processing in aphasia using paradigms that use more complex stimuli and/or that require integrated processing of music and language. In addition, future research can attempt to tease apart the neuroplastic effects of musical training from other confounding factors such as general intellectual ability.

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