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Grammatical Encoding and Learning in Agrammatic Aphasia: Evidence from Structural Priming

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Abstract

The present study addressed open questions about the nature of sentence production deficits in agrammatic aphasia. In two structural priming experiments, 13 aphasic and 13 age-matched control speakers repeated visually- and auditorily-presented prime sentences, and then used visually-presented word arrays to produce dative sentences. Experiment 1 examined whether agrammatic speakers form structural and thematic representations during sentence production, whereas Experiment 2 tested the lasting effects of structural priming in lags of two and four sentences. Results of Experiment 1 showed that, like unimpaired speakers, the aphasic speakers evinced intact structural priming effects, suggesting that they are able to generate such representations. Unimpaired speakers also evinced reliable thematic priming effects, whereas agrammatic speakers did so in some experimental conditions, suggesting that access to thematic representations may be intact. Results of Experiment 2 showed structural priming effects of comparable magnitude for aphasic and unimpaired speakers. In addition, both groups showed lasting structural priming effects in both lag conditions, consistent with implicit learning accounts. In both experiments, aphasic speakers with more severe language impairments exhibited larger priming effects, consistent with the "inverse preference" prediction of implicit learning accounts. The findings indicate that agrammatic speakers are sensitive to structural priming across levels of representation and that such effects are lasting, suggesting that structural priming may be beneficial for the treatment of sentence production deficits in agrammatism.

Keywords

structural priming; thematic priming; thematic mapping; sentence production; agrammatic aphasia

Introduction

Structural priming has played a central role in the development of models of normal sentence production (Pickering & Ferreira, 2008). For example, priming of syntactic

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structures without overlap of lexical items implies that people have mental representations of abstract syntax independent of lexical items (Bock, 1986, 1989; Bock & Loebell, 1990). Further, the results of structural priming studies have contributed substantially to the understanding of how conceptual information (e.g., animacy, thematic roles) is mapped onto syntactic structure during sentence production (Bock, Loebell, & Morey, 1992; Branigan, Pickering, & Tanaka, 2008; Cai, Pickering, & Branigan, 2012; Köhne, Pickering, & Branigan, 2014; Pappert & Pechmann, 2014). In recent years, structural priming has also been argued to play a critical role in implicit language learning throughout the lifespan (Chang, Dell, & Bock, 2006; Dell & Chang, 2014). However, structural priming has been relatively little-used to investigate the nature of sentence deficits in aphasia (though see (Cho & Thompson, 2010; Hartsuiker & Kolk, 1998; Marin & Schwartz, 1998; Saffran & Martin, 1997)). Structural priming studies with aphasic speakers have the potential to elucidate the nature of sentence production impairments and also inform models of normal sentence production. The present study used structural priming to address three questions about sentence production in aphasia and its implications for normal processing. First, we tested whether agrammatic speakers, like unimpaired speakers, form representations of the mapping between thematic and syntactic structure during sentence production. Second, we investigated whether aphasic speakers show lasting priming effects, consistent with intact implicit language learning ability. Third, we tested the hypothesis that more severe language impairments would be associated with larger priming effects, consistent with error-based learning accounts of structural priming (Chang et al., 2006; Dell & Chang, 2014).

Approximately 25% of stroke survivors with aphasia exhibit *agrammatism* (Pedersen, Vinter, & Olsen, 2004), which is characterized by nonfluent language production with syntactically simple utterances and frequent grammatical errors (Bastiaanse & Thompson, 2012). Grammatical impairments in agrammatic aphasia affect several aspects of language production. Individuals with agrammatic aphasia have greater difficulty producing sentences with complex verb-argument structures (e.g., dative sentences) compared to those with simpler structures (e.g., intransitive and transitive sentences) (Cho-Reyes & Thompson, 2012; Thompson, Lange, Schneider, & Shapiro, 1997). They also have difficulty producing syntactically complex sentences such as passives and embedded clauses (Caplan & Hanna, 1998; Cho-Reyes & Thompson, 2012; Faroqi-Shah & Thompson, 2003). On some theories, agrammatic sentence production deficits stem from an underspecification of linguistic representations (Friedmann & Grodzinsky, 1997), precluding the ability to generate fully-specified grammatical sentences, whereas other accounts link these deficits to impaired grammatical encoding, i.e., inability to implement grammatical representations in real-time (Cho & Thompson, 2010; Lee, Yoshida, & Thompson, 2015; Linebarger, Schwartz, Romania, Kohn, & Stephens, 2000).

One goal of research on language production in aphasia is to situate these deficits within psycholinguistic models of language production, which include stages such as message formation, lexical selection, grammatical function assignment, and morphosyntactic encoding (Bock & Ferreira, 2014; Bock & Levelt, 1994) and, in turn, to use aphasic deficit (and learning) patterns to inform these models. Agrammatic speakers frequently produce role reversal errors in semantically-reversible sentences (e.g., *The boy was chased by the girl* for *The girl was chased by the boy*) (Cho & Thompson, 2010; Saffran, Schwartz, & Marin, 1980; Thompson & Lee, 2009), suggesting deficits in the mapping from thematic roles (e.g., Agent, Theme) to syntactic structures (grammatical functions such as subject and object, or syntactic positions defined configurationally) (Bastiaanse & van Zonneveld, 2005; Cho & Thompson, 2010; Saffran et al., 1980; Schwartz, Linebarger, Saffran, & Pate, 1987; Schwartz, Saffran, Fink, Myers, & Martin, 1994; Thompson & Lee, 2009). In contrast, agrammatic speakers tend to exhibit relatively spared use of animacy information during sentence production, producing few role-reversal errors in semantically-irreversible sentences in which the subject and object have different animacy features (e.g., *The boy painted the picture*) (Saffran et al., 1980). Models of normal sentence production differ with respect to how conceptual-semantic information (thematic roles, animacy) is mapped onto syntactic structure (Bock et al., 1992; Branigan et al., 2008; Cai et al., 2012; Köhne et al., 2014; Pappert & Pechmann, 2014), and the abovementioned findings from aphasia suggest distinct mapping processes for thematic roles and animacy. Other errors produced by agrammatic speakers, such as omission and substitution of function words and grammatical morphology, point to deficits in morphosyntactic encoding (Caplan & Hanna, 1998; Faroqi-Shah & Thompson, 2003). Many individuals with agrammatic aphasia exhibit impairments in both thematic mapping and morphosyntactic encoding (Thompson et al., 2013); however, these substages of sentence production can be selectively impaired (Nespoulous et al., 1988), consistent with the distinct representation of these substages in models of normal sentence production.

Structural priming studies have provided some insight into the nature of agrammatic sentence production deficits. These studies have generally found intact structural priming effects in aphasic speakers, indicating a preserved ability to access and generate syntactic representations during sentence production in the face of otherwise impaired ability to generate grammatical sentences. Saffran and Martin (1997) examined structural priming in five participants with varying aphasia types. Participants described pictures after repeating transitive (active, passive) or dative prime structures. Priming was found for transitive structures, that is, more passive sentences were produced following passive vs. active primes and vice versa. No priming was found for dative structures; however, dative sentence production significantly increased in a sentence elicitation task administered before and after the experiment. In another study, Hartsuiker and Kolk (1998) assessed priming of transitive and dative structures in 12 Dutch-speaking agrammatic aphasic and 12 age-matched control participants. The authors manipulated experimental instructions across three sessions: participants were told to repeat sentences and 1) describe pictures to aid memory, 2) describe pictures without a memory task, and 3) reuse the prime structures to describe pictures. Control participants exhibited significant priming effects only with explicit instructions to reuse the previous structure, whereas aphasic speakers exhibited priming effects of similar magnitude across structures and test sessions. In a third study, Marin and Schwartz (1998) examined priming of closed-class words and grammatical morphology in six individuals with mild agrammatic aphasia and nine unimpaired adults. Both participant groups evinced priming for prepositions in locative phrases (e.g., The man was **in** the car vs. The man was **behind** the car), whereas agrammatic but not unimpaired speakers exhibited priming for verb tense morphology (e.g., *The sailor* ***boarded*** *the ship* vs. *The sailor* ***will board*** *the ship*). Finally, we (Cho & Thompson, 2010) combined a picture description priming task with an eyetracking-while-speaking paradigm to examine production of semantically-reversible transitive (active, passive) sentences in nine agrammatic aphasic speakers. Intact structural priming effects were found for passive sentences, indicating that agrammatic speakers could encode and accurately produce the morphosyntax of passive sentences. However, agrammatic speakers produced role-reversal errors at a high rate, suggesting deficits in thematic mapping and a relative insensitivity to priming at this level of representation.

The present study (Experiment 1) further investigated thematic mapping in agrammatic aphasia, examining thematic priming with and without animacy cues in dative structures. Priming of thematic representations, independent of phrase structure, has been shown for healthy speakers (Bernolet, Hartsuiker, & Pickering, 2009; Carminati, van Gompel, Scheepers, & Arai, 2008; Chang, Bock, & Goldberg, 2003; Hare & Goldberg, 1999; Köhne et al., 2014; Pappert & Pechmann, 2014; Salamoura & Williams, 2007). Chang and colleagues (2003) examined priming of sentences (e.g., 1) which are syntactically similar (NP V NP PP), but differ in the postverbal mapping between thematic roles and syntactic structures (Theme-Location vs. Location-Theme).The authors found that the Theme-Location structure was elicited significantly more frequently following Theme-Location, compared to Location-Theme, primes, and vice versa. The authors suggested that thematic priming effects emerge only for sentences that share a phrase structure (Chang et al., 2003). However, there is evidence suggesting that thematic mappings can be primed despite syntactic dissimilarities between prime and target sentences (Bernolet et al., 2009; Carminati et al., 2008; Hare & Goldberg, 1999; Pappert & Pechmann, 2014; Salamoura & Williams, 2007). For example, Hare and Goldberg (1999; cf. Salamoura & Williams, 2007) examined priming of dative structures using prepositional object (PO; 2a), double-object (DO; 2b), and provide-type sentences (2c). Provide-type sentences share a syntactic structure with PO sentences (NP V NP PP) but a thematic mapping with DO sentences (Recipient-Theme). The authors found priming from provide-type structures to DO but not PO structures. Animacy features have also been shown to affect structural priming in unimpaired speakers (Bock et al., 1992; Branigan et al., 2008). However, thematic priming has been shown to persist even when potential confounds with animacy are controlled (i.e., when the Recipient and Theme are matched with respect to animacy) (Köhne et al., 2014).

1) **a.** The maid rubbed polish into the table.

b. The maid rubbed the table with the polish.

2) **a.** The man gave a blanket to the woman.

b. The man gave the woman a blanket.

c. The man provided the woman with a blanket.

These effects demonstrate that normal sentence production is guided by representations of the mapping between thematic and syntactic structure. However, it has not been determined whether this is the case in agrammatism. The prevalence of role-reversal errors, particularly in semantically-reversible sentences, is consistent with the possibility that thematic representations do not guide agrammatic sentence production. However, evidence from eye movements during online sentence production suggests an alternative hypothesis, namely that agrammatic speakers have intact representations of thematic mappings, even for structures that they do not correctly encode (Cho & Thompson, 2010; Lee & Thompson, 2011a, 2011b). For example, Cho and Thompson (2010) showed increased processing costs (longer gaze durations) for passives with role reversals as compared to correct passives. The results suggest that aphasic speakers may be sensitive to mappings between thematic roles and syntactic structures, but unable to use this information to correctly encode complex sentences. Thus, Experiment 1 used structural priming to examine the mapping between thematic roles and syntactic structure in agrammatic and unimpaired speakers. We expected that unimpaired speakers would exhibit priming for the mapping between thematic roles and syntactic structure, even in the absence of animacy cues (cf. Köhne et al., 2014). For agrammatic speakers, if sentence production processes are guided predominantly by animacy features, we expected priming only in the presence of animacy cues. Alternatively, if access to thematic representations is intact, thematic priming effects were predicted, regardless of animacy cues.

In addition, the mechanisms of language (re)learning in agrammatic aphasia are not well-understood. Some studies suggest that individuals with agrammatic aphasia show retained ability to learn novel linguistic sequences, including artificial grammars (Schuchard & Thompson, 2014, in press), whereas other studies report learning impairments (Christiansen, Louise Kelly, Shillcock, & Greenfield, 2010; Zimmerer, Cowell, & Varley, 2014). In Experiment 2, we examined implicit language learning abilities by testing the lasting effects of structural priming (i.e., with two or four intervening sentences between prime and target sentences). In healthy speakers, priming effects can persist for 10 intervening trials or more, typically when there is no open-class lexical overlap between the prime and target sentences (Bock, Dell, Chang, & Onishi, 2007; Bock & Griffin, 2000; Ferreira, Bock, Wilson, & Cohen, 2008; Hartsuiker, Bernolet, Schoonbaert, Speybroeck, & Vanderelst, 2008). These lasting priming effects have been argued to reflect implicit language learning. Experiment 2 tested the hypothesis that implicit learning mechanisms are intact in agrammatism, thus resulting in lasting priming effects. Such a finding, together with those from Experiment 1, would suggest that structural priming may be viable for treating sentence production deficits and promote lasting improvements.

Lastly, Experiments 1 and 2 examined the relationship between structural priming and the severity of linguistic impairments in aphasia, in order to test the predictions of an error-based implicit learning account of structural priming (Chang et al., 2006; Dell & Chang, 2014). Accordingly, listeners make predictions when they hear sentences as to how the sentence will unfold structurally, e.g., when the fragment *The man gave ...* is heard, a prediction that it will be completed as a DO structure may be formulated (e.g., 2b). If the prediction is incorrect (e.g., if a PO structure such as 2a is heard), this prediction error leads to a change in the language system such that the PO structure will be more expected in the future. Prediction and production are proposed to emerge from the same linguistic sequencing system; thus error-based learning also results in a greater tendency to produce PO structures. This model predicts an *inverse preference effect*, in which the magnitude of priming (i.e., learning) increases with greater prediction error. Accordingly, increased priming effects have been found in populations with language impairments as compared to unimpaired speakers (Anderson & Conture, 2004; Hartsuiker & Kolk, 1998; Tsiamtsiouris & Cairns, 2009) as well as in unimpaired speakers for rare vs. common structures (Bernolet &

Hartsuiker, 2010; Jaeger & Snider, 2013). Most relevant to the present study, Hartsuiker and Kolk (1998) found more reliable priming effects in agrammatic than age-matched control speakers when participants were not explicitly instructed to reuse the prime structure. The present study tests two predictions of the implicit learning model: 1) priming effects should be larger in agrammatic speakers than in controls (cf. Hartsuiker & Kolk, 1998); 2) within the group of aphasic speakers, larger priming effects should be found for those with greater language impairments. On a clinical level, such findings would suggest that agrammatic speakers with more severe language deficits would potentially draw greater benefits from priming-based approaches to language treatment.

To summarize, the present study includes two experiments designed to test (1) whether thematic information is used to build sentences in agrammatic aphasia (in which case intact thematic priming effects are expected), or whether only animacy information is used (in which case thematic priming effects are expected only with reliable animacy cues) (Experiment 1), and (2) whether structural priming effects are long-lasting, reflecting implicit learning (Experiment 2). In both experiments we also examined whether the severity of language impairment is associated with increased priming, consistent with the "inverse preference" effect predicted by implicit learning accounts of structural priming.

Experiment 1

Experiment 1 examined structural and thematic priming in agrammatic and unimpaired speakers.

Materials and Methods

Participants—Thirteen healthy control individuals and 13 individuals with agrammatic aphasia participated in the study. The control participants (7 female, 6 male) were recruited from the Northwestern University and greater Chicago community, and the agrammatic participants (4 female, 9 male) were recruited from the Aphasia and Neurolinguistics Research Laboratory and Northwestern Speech, Language and Learning clinic. The two groups were matched for age (M = 58, range: 33 – 76 for the control group; M = 59, range: 33 – 75 for the aphasic group) (Z = −1.212, p = .225, Mann-Whitney U Test) and education (M = 17, range: 12 – 21 for both participant groups) (Z = −1.270, p = .204, Mann-Whitney U Test). All agrammatic participants suffered a single thromboembolic stroke in the left hemisphere except one whose stroke was in the right hemisphere (A7)[1], with an average of 8.3 years post-stroke (range: 2.3 – 21.2). All participants were right-handed except one (A4) and monolingual speakers of English with normal or corrected-to-normal hearing and vision except one agrammatic participant (A11) who was a Spanish-English bilingual speaker. Though his first language was Spanish, English had been his primary language since the age of four and it was preserved to a greater extent than Spanish post-stroke. None of the participants reported any prior history of neurological, psychiatric, speech-language, or learning disorders.

[1]A7 showed crossed-aphasia, with agrammatic language deficits resulting from a right hemisphere stroke.

All aphasic participants presented with mild-to-moderate agrammatic aphasia, based on performance on the *Western Aphasia Battery-Revised* (WAB-R) (Kertesz, 2006) and the *Northwestern Assessment of Verb and Sentences* (NAVS) (Thompson, 2011). A summary of language testing scores is provided in Table 1. Aphasia Quotients (AQs) derived from the WAB ranged from 71.7 to 89.6, indicating mild-to-moderate aphasia. Scores on WAB subtests indicated effortful and nonfluent spontaneous speech marked by reduced syntactic complexity and impaired grammatical morphology (Fluency subtest: M = 5.1), relatively preserved auditory comprehension (M = 9.0), and mild-to-moderate difficulty with repetition (M = 8.3) and naming (M = 8.8). Results from the NAVS revealed further characteristics of agrammatism. Despite good performance on the Verb Comprehension Test (M ≥ 98%), agrammatic participants exhibited impaired performance on the Verb Naming Test (VNT): verbs with three arguments were named less accurately (M = 75%) compared to one- and two-argument verbs (M = 92% for each).[2] Similarly, scores from the Argument Structure Production Test (ASPT) indicated greater impairment in sentence production with three-argument verbs (M = 78%) compared to one- and two-argument verbs (M =100% and 98%, respectively). Because the present study examines dative sentence production, we compared the agrammatic participants' performance on three-argument sentences on the ASPT to that of a cohort of 26 unimpaired older adults; all agrammatic participants were found to have significant impairments in this domain ($|t|$'s > 2, p's < .05, Crawford-Howell test). On the Sentence Production Priming Test (SPPT) and the Sentence Comprehension Test (SCT), the agrammatic participants exhibited greater difficulty with noncanonical sentences (i.e., passives, object-wh questions, object relative clauses) compared to canonical sentences (i.e., actives, subject-wh questions, subject relative clauses) in both production and comprehension (SPPT noncanonical M = 48%; canonical M = 84%; SCT noncanonical M = 69%; canonical M = 83%).

Stimuli—The experimental stimuli consisted of visually- and auditorily-presented prime sentences and visual arrays containing words that could be combined to create dative sentences. The prime sentences included prepositional object (PO; 3a) and double-object (DO; 3b) sentences as well as provide-type primes (3c-d). In provide-type primes, the animacy of the Recipient was manipulated (animate in (3c); inanimate in (3d)) to control possible effects of animacy on priming (cf. Köhne et al. 2014). The PO condition (3a) served as a baseline to which others were compared. DO sentences (3b) were used to examine structural priming effects (i.e., a higher rate of DO responses following DO vs. PO primes), whereas provide-type primes were used to examine thematic priming effects.

(3) **a.** Baseline (PO): The lawyer is bringing the document to the partner.

b. Structural (DO): The lawyer is bringing the partner the document.

c. Thematic (provide)-animate: The mayor is providing the minister with the donations.

[2]The one- and two-argument verbs included on the VNT were matched for lexical frequency. Notably, however, the three-argument verbs were more frequently-occurring than the one- and two-argument verbs (Thompson, 2011). Thus, the greater impairment on three- vs one- and two-argument verbs cannot be attributed to frequency.

d. Thematic (provide)-inanimate: The mayor is providing the chapel with the donations.

Prime sentences were recorded by a male native speaker of English at a normal rate. For the DO and PO prime conditions, sentences were prepared using six dative verbs (*assign, award, bring, lend, promise, send*); whereas, six provide-type verbs (*burden, credit, present, provide, supply, trust*) were used for the provide-verb conditions. The verbs were selected based on the classifications in Levin (1993) and reliable priming found in previous studies (Bock & Griffin, 2000; Hartsuiker & Kolk, 1998; Pickering & Branigan, 1998) (Hare & Goldberg, 1999; Salamoura & Williams, 2007). Two sets of 36 nouns (24 animate and 12 inanimate) were also selected and combined in triplets (Agent, Theme, Recipient) with each verb, resulting in 12 DO/PO sentence pairs and 12 provide animate/inanimate prime sentence pairs (see Appendices 1 and 2). The dative and provide-type verbs as well as the nouns were matched for the mean $\log_{10}$ lemma frequency (verbs: $t(22) = .464$, $p = .647$; nouns: agent: $t(22) = -1.028$, $p = .315$, theme = $t(22) = .996$, $p = .330$, recipient = $t(22) = -.342$, $p = .736$). The nouns were also matched for the number of syllables (agent: $t(22) = 1.076$, $p = .294$, theme = $t(22) = .000$, $p = 1.000$, recipient = $t(22) = 1.787$, $p = .088$).

Target stimuli included six alternating dative verbs (*give, hand, offer, pass, sell*, and *show*) and 72 nouns (48 animate, 24 inanimate). Each verb was combined with four noun triplets (Agent, Theme, Recipient), resulting in a total of 24 target DO/PO sentence pairs (e.g., *the priest is giving the orphan the gift* or *the priest is giving the gift to the orphan*). There was no lexical overlap between the prime and target stimuli. All experimental stimuli were normed with ten young normal speakers. Prime sentences were included if they received a mean of 6 or above in a 7-point scale acceptability judgment task, with 7 being the most acceptable; whereas, target stimuli were included in the experiment if they elicited dative sentences at least 80% of the time.

Visual arrays were developed for each target sentence, with each verb and associated set of nouns displayed in written form (34 point font). The verb, presented in the progressive form (e.g., *giving*) to reduce aphasic speakers' verb inflection difficulty, was always displayed on the left and nouns were on the right (one on the top and two on the bottom) (see Figure 1). Participants were required to combine the words in the array with function words, which were not included.

Half of the target visual arrays (n = 12) were paired once each with a DO and a PO prime, and the other half (n=12) were paired once each with a provide-animate and a provide-inanimate prime, resulting in 48 experimental prime-target pairs. Lexical items in the target sentences paired with dative and provide-type primes were matched for the $\log_{10}$ lemma frequency of nouns in each thematic role (agent: $t(22) = -1.607$, $p = .122$; theme = $t(22) = -.040$, $p = .968$; recipient = $t(22) = .118$, $p = .907$) and the mean number of syllables (agent: $t(22) = -.611$, $p = .548$; theme = $t(22) = -.561$, $p = .581$; recipient = $t(22) = -.294$, $p = .771$).

An additional 96 filler prime-target pairs were prepared. Filler prime sentences included a range of intransitive constructions (e.g., the gray mouse is jumping; the jumping mouse is gray; the chemist is blinking cautiously; the chemist is cautiously blinking). None of the lexical items used in the experimental stimuli were included in the filler sentences.

To distract from the priming manipulation, memory probes (n=36) were included which asked participants to identify whether or not they had seen a particular word visually presented on the screen during the experiment, with auditory instructions: 'Have you seen this word before?' Participants responded by saying 'yes' or 'no'. All participants were able to produce reliable yes/no responses. Half of the words were randomly selected from the filler stimuli (9 adjectives and 9 nouns), and the other half contained adjectives and nouns that were not included in the experiment. Memory probes did not include any words used in the experimental pairs.

The 48 experimental and 96 filler prime-target pairs as well as 36 memory probes were split into two pseudorandomized lists, each of which contained six experimental prime-target pairs per prime condition (n = 24 total experimental items). Each prime-target pair appeared once in each list, with memory probes included after 25% of trials (pseudorandomly selected). Care was taken to avoid repetition of prime conditions as well as target verbs. Any two trials of the same condition were separated by two to four intervening trials, and any two trials with the same target verb were separated by at least one intervening trial. The order of lists was counterbalanced across participants.

Procedures

Experiment 1 was conducted in two separate sessions, each including administration of a single stimulus list. The two sessions were separated by at least 10 days[3], with an average of 13 days (range = 10 – 19), to reduce repetition effects. Each session lasted approximately 45 minutes for the control participants and 60 to 90 minutes for the agrammatic participants. Prior to the first session, all agrammatic participants were tested for reading comprehension of verbs and nouns used for the experimental (and some filler) stimuli to ensure that any difficulty understanding prime sentences and producing target sentences did not stem from a lexical impairment. All agrammatic participants were able to read and comprehend the tested items at a rate of 90% or above.

The experiment was presented on a Mac Book laptop computer using SuperLab 4.5 (Abboud, Schultz, & Zeitlin, 2008); the entire session was audio-recorded using Praat 5.2 (Boersma & Weenink, 2011). Participants were seated in front of the computer screen and told that they would be participating in a memory recognition test in which they would also repeat and produce sentences. Participants were encouraged to pay attention to the sentences because on upcoming memory probes they would need to identify whether or not they had seen a particular word during the experiment. Prior to the experiment, participants were familiarized with the procedures using ten practice trials.

An example trial is provided in Figure 1. Each prime-target trial began with a blank white screen which appeared for 1000 milliseconds, with an auditory instruction to 'Repeat after

[3]This number was established based on the finding in Kaschak, Kutta, and Schatschneider (2011) that structural priming can last up to a week in neurologically healthy speakers.

me'. Then, a prime sentence was presented both visually and auditorily, which remained until participants repeated it and advanced to the next trial by clicking with the mouse. After 300 ms of fixation, a target visual panel was presented simultaneously with a beep. Participants were asked to produce a grammatical sentence including these words.

Data analysis

Response coding—To ensure priming effects between the prime-target pair, correct repetition of prime sentences was essential. Hence, all responses preceded by an incorrectly-repeated prime sentence were eliminated from data analysis.

Responses were scored as DO, PO, or "other." When participants produced more than one attempt for a single response, only the first attempt was scored. An attempt was defined as a sentence containing at least a subject, a verb, and an object. A response was scored as DO if the phrase structure followed an NP V NP NP order and the thematic roles for the post-verbal nouns followed a Recipient-Theme order. A response was scored as PO if it contained an NP V NP PP structure and a Theme-Recipient order for the post-verbal nouns. For agrammatic participants, omission or addition of prepositions was not accepted because this was critical for the experiment; however, preposition substitutions were accepted for the Recipient PP in PO responses: prepositions that could be used with animate nouns (e.g., *for, with, of* for *to*) were accepted, but not others (*in, at*). Omission of a determiner in a noun phrase and substitution of any verb form for the target verb (e.g., *is giving, giving, gives, gave*) was allowed. Phonological paraphasias were accepted if 70% or more phonemes of a target word were correctly produced. Responses that could not be scored either as DO or PO were scored as "other." "Other" responses included grammatical sentences containing a phrase structure other than a dative structure (e.g., transitive, embedded sentences) as well as ungrammatical sentences.

Statistical analyses—To examine overall response accuracy, the number of correct dative responses (DO + PO) was divided by the total number of scorable responses (DO, PO, and "other") in each condition. Overall accuracy was compared between participant groups using the Mann-Whitney U test.

Analyses of priming effects were performed using correct dative responses only, excluding "other" responses. Following Pickering, Branigan, and MacLean (2002) the proportion of DO responses was computed for each participant and prime condition by dividing the number of DO responses by the total number of DO plus PO responses produced. The magnitude of *structural, thematic-animate,* and *thematic-inanimate* priming was calculated for each participant by subtracting the proportion of DO responses in the PO condition from, respectively, the proportion of DO responses in the DO, provide-animate, and provide-inanimate conditions. In the correlation analyses of priming magnitude described below, the proportion of DO responses underwent the empirical logit transformation (i.e., log odds of a DO response).

Statistical analyses of priming effects were conducted using mixed-effects logistic regression. First, data were modeled separately for each participant group in order to test for priming effects across conditions. In these models, the dependent variable was whether the participant had produced a DO (vs. PO) response, and the independent variable was prime type (DO, PO, provide-animate and provide-inanimate). A third model compared priming effects across participant groups, and independent variables were prime type, group, and their interaction. In all models, by-participant slopes and intercepts were included, and all variables were simple-coded, i.e., each level of a factor was compared to a reference level, with the grand mean being the intercept across levels.[4]

To examine the relationship between priming effects and the degree of aphasic language deficits, correlations (Spearman *r*, one-tailed, FDR-corrected) were computed between priming effects and language measures: (1) WAB-R AQ, reflecting general aphasia severity; (2) production of three-argument sentences on the NAVS Argument Structure Production Test (ASPT); and (3) production of noncanonical sentences on the NAVS Sentence Production Priming Test (SPPT).

Results

Overall accuracy of target responses—Four responses (0.6%) from the control group and ten responses (1.6%) from the agrammatic group were discarded due to errors in repetition of the prime sentences. For the remaining responses, Table 2 summarizes response accuracy for each participant group. Within each participant group the proportion of correct dative responses did not differ across conditions (p's > .1, Mann-Whitney U Test). As expected, controls produced significantly more correct dative sentences than agrammatic speakers ($p < .05$, Mann-Whitney U Test).

Analyses of priming effects—Table 2 shows the mean proportion of DO responses out of all correct dative responses in each prime condition, as well as the magnitude of structural, thematic-animate, and thematic-inanimate priming in each participant group. The results of the mixed-effects regression analyses of priming effects are summarized in Table 3. Overall, control speakers were equally likely to produce DO and PO structures ($t = .452$, $p > .1$). They produced more DO responses following DO, provide-animate, and provide-inanimate primes as compared to PO primes (t's > 3.7, p's < .001), reflecting significant structural, thematic-animate and thematic-inanimate priming effects, respectively. No significant differences were observed between DO, provide-animate, and provide-inanimate primes ($|t|$'s < 1.1, p's > .1). In contrast to controls, speakers with agrammatic aphasia produced fewer DO than PO responses overall ($t = -3.857$, $p < .001$). They were more likely to produce DO responses following DO and provide-inanimate primes as compared to PO primes (t's > 2.1, p's < .05); however, the rate of DO responses following provide-animate primes did not reliably differ from PO primes ($t = 1.014$, $p = .311$), and was significantly lower than DO primes ($t = -2.019$, $p < .05$). No other differences were observed between prime types ($|t|$'s < 1.4, p's >.1). Thus, agrammatic speakers also exhibited structural and thematic-inanimate priming effects, but not reliable thematic-animate priming effects. The model of priming effects across participant groups (Table 3) revealed that agrammatic participants produced a lower rate of DO responses overall than controls ($t = -3.366$, $p <$

[4]Because the experiments aimed to replicate priming effects that were well-established in healthy speakers, the question of across-item generalization was of relatively low importance for the present study, and thus we did not include random effects for items in the analyses.

0.001). The magnitude of structural priming (i.e., the rate of DO responses in the DO vs. PO condition) and thematic-inanimate priming (the rate of DO responses in the provide-inanimate vs. PO condition) did not differ across participant groups ($|t|$'s < 1, p's >.1). However, control participants showed a larger magnitude of thematic-animate priming (the rate of DO responses in the provide-animate vs. PO condition) as compared to agrammatic speakers ($t = -1.986$, $p < .05$).

A significant negative correlation was found between aphasia severity and thematic-animate priming effects ($r = -0.79$, $p < .01$) and marginally significant negative correlations were found for structural ($r = -0.51$, $p = .058$) and thematic-inanimate priming effects ($r = -0.47$, $p = .068$), indicating that participants with more severe aphasia (lower WAB-R AQ) showed greater priming effects than those with less severe language impairments. Three-argument sentence production ability (NAVS ASPT) also was negatively correlated with priming effects in all conditions (structural: $r = -0.65$, $p < .05$; thematic-animate: $r = -0.81$, $p < .01$; thematic-inanimate: $r = -0.63$, $p < .05$) and marginally significant negative correlations were found between noncanonical sentence production ability (NAVS SPPT) and thematic-animate ($r = -0.54$, p = .058) and thematic-inanimate priming effects ($r = -0.47$, $p = .068$), but not with structural priming ($r = -0.24$, $p = 0.22$).

Discussion

The results of Experiment 1 revealed structural priming for dative structures in speakers with agrammatic aphasia as well as age-matched controls. These findings join many reports of structural priming in unimpaired speakers (see review in Pickering & Ferreira, 2008), and are also consistent with two previous studies that examined priming of datives in aphasic speakers, one of which found significant immediate (trial-to-trial) priming effects (Hartsuiker & Kolk, 1998) and one of which found significant cumulative, but not immediate, priming effects (Saffran & Martin, 1997).

Unimpaired speakers also showed thematic priming effects, i.e., thematic role order. The magnitude of these effects did not significantly differ from their structural priming effects. Further, the magnitude of thematic priming was similar regardless of the presence of animacy cues, suggesting that animacy did not have an independent effect on thematic mapping. These findings are consistent with previous reports of thematic priming in healthy speakers (Chang et al., 2003; Hare & Goldberg, 1999; Köhne et al., 2014; Pappert & Pechmann, 2014; Salamoura & Williams, 2007).

In agrammatic speakers, significant thematic priming effects were observed in the inanimate condition, although a trend towards thematic priming was observed in the animate condition as well. The relatively high degree of inter-individual variability in the thematic-animate condition (SD = 0.21, vs. 0.12 in the thematic-inanimate condition) likely contributed to the lack of significant priming effects in this condition. Notably, the magnitude of priming was the same regardless of animacy, indicating that at least some agrammatic speakers, like unimpaired speakers, are not influenced by animacy in thematic priming, in contrast with common animacy effects observed in individuals with aphasia in other tasks (e.g., Saffran et al., 1980).

These findings differ from those reported by Cho and Thompson (2010), who found impaired thematic mapping of passive sentences in agrammatic speakers, likely associated with the added difficulty of thematic mapping in complex structures. However, it is noteworthy that Cho and Thompson found intact morphosyntactic priming, indicating that agrammatic individuals show successful structural priming even in sentences that are otherwise difficult to produce.

The magnitude of priming was similar across participant groups, except in the thematic-animate condition, in which unimpaired speakers showed larger priming effects as compared to agrammatic speakers. This finding was unexpected, given our prediction of an inverse preference effect (i.e., larger priming effects for agrammatic speakers) as seen in previous studies (Hartsuiker & Kolk, 1998). Notably, however, several agrammatic participants (7 of 13) evinced relatively mild agrammatism, likely contributing to more normal-like priming patterns. In addition, our experimental task, which minimized lexical retrieval demands, may have contributed to normal-like performance (in contrast with the picture description task of Hartsuiker and Kolk, 1998). However, speakers with more severe language deficits showed larger priming effects. As predicted, moderate to strong negative correlations ($-0.81 < r < -0.47$) were found between priming effects and measures of aphasia severity, dative sentence production ability, and noncanonical sentence production ability; the sole exception was a non-significant correlation between structural priming effect size and noncanonical sentence production ability. Thus, our prediction of an inverse preference effect received partial support from Experiment 1: such an effect was evident within the group of agrammatic speakers, but not in the comparison between agrammatic and control speakers.

Experiment 2

Experiment 2 investigated implicit language learning ability by examining the lasting effects of structural priming in lags of two (Lag 2) and four (Lag 4) intervening sentences in aphasic and unimpaired speakers.

Materials and Methods

Participants—The participants in Experiment 2 were the same as in Experiment 1.

Stimuli—As in Experiment 1, stimuli consisted of prime sentences, presented both visually and auditorily, and visually-presented word arrays to test production of dative sentences. Prime sentences were recorded by a male native speaker of English (the same as in Experiment 1) at a normal rate. The sentences were DO and PO structures, each containing one of six dative verbs (*bake, buy, feed, serve, teach*, and *throw*) that were selected based on the verb classification in (Levin, 1993) and previous priming studies (Bock & Griffin, 2000; Hartsuiker et al., 2008; Pickering & Branigan, 1998), and a set of 72 nouns (48 animate and 24 inanimate). Each of the six verbs was paired with four noun triplets (Agent, Recipient, Theme), resulting in 24 DO/PO prime sentence pairs (see Appendices 3-4). Half of the primes were used in the Lag 2 condition and the other half were used in Lag 4. Across conditions (Lag 2 vs. Lag 4), the nouns within each participant role were matched for the $\log_{10}$ lemma frequency (agent: $t(22) = -.699$, $p = .492$; theme = $t(22) = -.532$, $p = .600$;

recipient = $t(22) = -.842$, $p = .409$) and the mean number of syllables (agent: $t(22) = -.561$, $p = .581$; theme = $t(22) = .000$, $p = 1.000$; recipient = $t(22) = .304$, $p = .764$).

The target visual arrays each contained one verb and three nouns as in Experiment 1; participants were required to add function words, which were not pictured, to produce grammatical dative sentences. The arrays contained the same six verbs as in Experiment 1 (*give, hand, offer, pass, sell*, and *show*) and 72 nouns (48 animate and 24 inanimate). There was no lexical overlap between the prime and target stimuli. Each verb was paired with four noun triplets (Agent, Theme, Recipient), resulting in 24 target dative (DO/PO) sentence pairs. Half of the target arrays (n = 12) were paired with the prime sentences for Lag 2, and the other half (n=12) were paired with the prime sentences for Lag 4. The target sentences used for Lag 2 and Lag 4 were matched for the $\log_{10}$ lemma frequency of nouns used in each participant role (agent: $t(22) = .549$, $p = .589$; theme = $t(22) = -.119$, $p = .906$; recipient = $t(22) = -.467$, $p = .645$) and the mean number of syllables (agent: $t(22) = -1.431$, $p = .167$; theme = $t(22) = -1.449$, $p = .161$; recipient = $t(22) = .928$, $p = .364$).

Intervening sentences (n=72) between prime and target trials consisted of intransitive sentences (e.g., the tiny puppy is barking; the barking puppy is tiny). Filler prime-target pairs (n= 72) also consisted of intransitive structures (e.g., the chemist is blinking cautiously; the chemist is cautiously blinking; the angel and the witch are screaming). Memory probes (n=32), like those used in Experiment 1, consisted of 16 words (nouns, adjectives) that appeared in the experiment and 16 that did not. None of lexical items used in the experimental stimuli were included in the lag sentences, fillers, or memory probes.

The 48 experimental and 72 filler prime-target pairs, 72 lag sentences, and 32 memory probes were split into two pseudorandomized lists. Each list contained six experimental prime-target pairs per prime condition (n = 24 total). Each prime-target pair appeared once in each list. Repetition of prime conditions as well as target verbs was minimized. Within each list, trials from the same condition were separated by at least two intervening trials, and trials with the same verb were separated by at least one trial. The order of lists was counterbalanced across participants.

Procedures—Experiment 2 was conducted in two separate sessions, as in Experiment 1, each including administration of a single list. The two sessions were separated by at least 10 days (M = 12.8, range = 10 – 18). Each session for Experiment 2 lasted approximately 45 minutes for the control participants and 70 to 100 minutes for the agrammatic participants. One list each from Experiments 1 and 2 was administered during each test day with the order of experiment and list counterbalanced. The time lapse between each experiment was 10 to 30 minutes.

Participants were provided with identical instructions as in Experiment 1. The experimental procedures were also the same as Experiment 1 except for the intervening trials between experimental prime and target pairs. Two or four sentences, depending on the condition (Lag 2 or Lag 4), were presented in the same manner as prime sentences, and participants were asked to repeat them. An example trial appears in Figure 2.

Data Analysis

Response coding: The criteria for scoring and coding responses used for Experiment 2 were identical to Experiment 1.

Statistical Analyses: Data were analyzed in the same manner as in Experiment 1. For the mixed-effects logistic regression models examining priming effects for each participant group, the dependent variable was response type, i.e., DO (vs. PO) production, and the independent variables were prime type (DO, PO), lag length (Lag 2, Lag 4), and their interaction. The third model compared priming effects across participant groups, and the independent variables were group, prime type, lag length, and their interactions. By-participant slopes and intercepts were included in all models and all variables were simple-coded. Finally, correlations were computed between the magnitude of priming in each condition and the severity of language impairments, using the same language measures and methods as in Experiment 1.

Results

Overall accuracy of target responses—Three (0.5%) and six (1%) trials for the control and agrammatic groups, respectively, were not analyzed due to incorrect repetition of prime sentences. Of the remaining responses, Table 4 summarizes the mean proportion of correctly produced target dative (DO + PO) responses in each condition for both participant groups. Within each participant group the proportion of correct dative responses did not differ across conditions (p's > .1, Mann-Whitney U Test), indicating that analyzable responses for priming effects in each condition were equally distributed. As in Experiment 1, controls produced significantly more correct dative sentences than agrammatic speakers ($p < .05$, Mann-Whitney U Test).

Analyses of priming effects—Table 4 provides the mean proportion of DO responses out of all correct dative responses, as well as the magnitude of priming in each Lag condition, for each participant group. The results of the mixed-effects regression analyses of priming effects are summarized in Table 5. Overall, control speakers were equally likely to produce DO and PO structures ($t = -0.351$, $p > .1$). They produced more DO responses following DO as compared to PO primes ($t = 4.879$, $p < .001$), reflecting significant structural priming. The rate of DO responses did not differ across Lags and there was no interaction between Lag and Prime Type ($|t|$'s < 1, p's > .1). Participants with aphasia were more likely to produce PO than DO structures ($t = -4.51$, $p < .001$), but like controls, they produced more DO responses following DO vs. PO structures ($t = 3.81$; $p < .001$), and showed no effect of Lag or interaction between Lag and Prime Type ($|t|$'s < 1.1, p's > .1). The model of priming effects across groups indicated that control speakers produced significantly more DO responses than agrammatic speakers overall ($t = -3.652$, $p < .001$), but the two groups did not differ significantly in the overall magnitude of structural priming, or in the relative magnitude of structural priming across lags ($|t|$'s < 1.3, p's > .1)

As in Experiment 1, significant negative correlations between aphasia severity and the magnitude of priming effects were found in Experiment 2. Participants with more severe aphasia (lower WAB-R AQ) had larger priming effects at Lag 2 ($r = -0.61$; $p <. 05$) but not

Lag 4 ($r = -0.18$; $p = 0.28$); a similar pattern of results emerged for production of three-argument sentences (NAVS) (Lag 2: $r = -0.56$; $p < .05$; Lag 4: $r = -0.25$; $p = 0.27$). However, greater impairments in noncanonical sentence production (NAVS) were associated with greater priming effects at Lag 2 ($r = -0.69$, $p < .05$) and Lag 4 ($r = -0.79$, $p < .01$).

Discussion

In Experiment 2, agrammatic, like control, speakers showed structural priming even with four sentences intervening between the prime and target, and the magnitude of priming was unchanged as the intervening period increased (two vs. four sentences). Such lasting priming effects in healthy speakers have been argued to reflect implicit learning rather than transient activation of primed structures (Bock et al., 2007; Bock & Griffin, 2000; Ferreira et al., 2008; Hartsuiker et al., 2008). Thus, in agrammatic speakers, these results are consistent with findings that implicit language learning ability may be spared (Schuchard & Thompson, 2014, in press) rather than impaired (Christiansen et al. (2010); Zimmerer et al. (2014).

The magnitude of priming did not differ between participant groups, possibly due to the high performance of several aphasic speakers, however, as in Experiment 1, larger priming effects were found in patients with more severe language impairments. Again, similar to Experiment 1, greater aphasia severity was associated with larger priming effects. Strong negative correlations ($-0.79 < r < -0.56$) were observed between priming at Lag 2 and measures of aphasia severity, dative sentence production, and noncanonical sentence production, whereas priming at Lag 4 correlated only with noncanonical sentence production ability. As in Experiment 1, these correlation results are generally consistent with an inverse preference effect.

General Discussion

This study used structural priming in order to address several open questions about sentence production processes in agrammatic aphasia and unimpaired adults. The first aim was to determine whether agrammatic speakers form thematic representations during sentence production. The second aim was to determine whether priming effects in agrammatic speakers are lasting, reflecting implicit learning. The third aim was to determine whether priming effects were inversely associated with language production ability, as predicted by implicit learning accounts of structural priming. In order to address these questions, Experiment 1 examined structural and thematic priming effects, whereas Experiment 2 examined lasting structural priming effects (i.e., with up to four intervening sentences). For both experiments, we examined the relationship between priming effect size and the severity of language impairments in agrammatic speakers.

We first review the overall patterns of performance found in the present study. As expected, the agrammatic group overall had significantly lower accuracy than the control group in both experiments, coinciding with sentence production ability noted on pretesting. On the Argument Structure Production Test (ASPT) of the NAVS the patient group performed at 78% correct (range: 58% to 92%) on three-argument sentences (e.g., NP V NP PP), as compared to averages of 100% and 98% correct production of one-and two-argument sentences, respectively, and all participants showed statistically significant impairments of three-argument sentence production as compared to a cohort of unimpaired adult speakers. Impaired production of three-argument sentences is characteristic of agrammatism and has been reported in several previous studies (Cho-Reyes & Thompson, 2012; Thompson et al., 1997).

In both experiments, the agrammatic speakers produced PO structures significantly more frequently than DO structures, whereas control speakers produced both structures with approximately equal frequency. In previous studies, Saffran and Martin (1997) and Hartsuiker and Kolk (1998) also reported numerical preferences for PO structures in agrammatic speakers. Agrammatic speakers' preference for PO vs. DO structures may be due to the relative linguistic complexity and markedness of DO structures. DO structures have a noncanonical mapping (Recipient-Theme), whereas PO structures have a canonical thematic mapping (Theme-Recipient). According to some transformational syntactic analyses (Larson, 1988), DO sentences are derived from PO sentences by syntactic movement. Further, DO structures are pragmatically marked, and are typically produced when the Recipient is more accessible than the Theme (Arnold, Losongco, Wasow, & Ginstrom, 2000; Clifton & Frazier, 2004).

Turning to the priming results, both unimpaired and aphasic participants showed structural priming effects in both experiments. These findings replicate the abundant evidence for structural priming in the normal literature (Bock, 1986; Pickering & Branigan, 1998; Pickering & Ferreira, 2008) and are consistent with the few studies in the literature focused on structural priming in agrammatic aphasia (Cho & Thompson, 2010; Hartsuiker & Kolk, 1998; Marin & Schwartz, 1998; Saffran & Martin, 1997).

Unimpaired speakers also showed priming for the mapping between thematic roles and syntactic representations (Experiment 1), i.e., priming between structures that share a thematic role order (Agent-Theme-Recipient or Agent-Recipient-Theme) but not phrase structure. These results are consistent with previous studies that found priming at the thematic level for unimpaired speakers (Bernolet et al., 2009; Carminati et al., 2008; Chang et al., 2003; Hare & Goldberg, 1999; Köhne et al., 2014; Pappert & Pechmann, 2014; Salamoura & Williams, 2007). In addition, they suggest that thematic priming effects can emerge even in structures that do not share a phrase structure (Bernolet et al., 2009; Carminati et al., 2008; Hare & Goldberg, 1999; Pappert & Pechmann, 2014; Salamoura & Williams, 2007), in contrast with some accounts of these effects (Chang et al., 2003).

No previous studies had examined priming at this level in agrammatic speakers. In the present study, agrammatic speakers evinced significant thematic priming effects only in the thematic-inanimate condition. In the thematic-animate condition, there was a trend towards priming that did not reach significance. The present findings suggest that sentence production in agrammatic aphasia is sensitive to priming of the mapping between thematic roles and syntactic structures. These findings suggest that agrammatic speakers do form abstract structural representations, including thematic representations, that guide sentence production, and are thus inconsistent with representational accounts of sentence production deficits (Friedmann & Grodzinsky, 1997). In contrast, they lend support to grammatical encoding accounts of agrammatism, and in particular are consistent with research suggesting that agrammatic speakers have intact access to thematic and syntactic information but difficulty implementing this information as sentence production unfolds (Cho & Thompson, 2010; Lee & Thompson, 2011a, 2011b; Lee et al., 2015).

In Experiment 1, the presence (or absence) of animacy cues did not affect the magnitude of thematic priming in either participant group. Historically, there has been a debate as to the role of event-specific semantic features (e.g., thematic roles) and intrinsic semantic features (e.g., animacy) in determining the mapping to syntactic structure (see discussion in Pickering & Ferreira, 2008). Convincing evidence has emerged that both types of semantic features can affect the choice of syntactic structures during production (Bock et al., 1992; Branigan et al., 2008; Köhne et al., 2014; Pappert & Pechmann, 2014) but further research is needed to determine their relative contributions. In agrammatism, role reversal errors observed in previous studies (e.g., Saffran et al., 1980) suggest that animacy might play a key role in guiding sentence production. However, the results of the present study instead emphasize the importance of thematic information in guiding sentence production in both unimpaired and aphasic speakers.

The results of Experiment 2 demonstrated that agrammatic, like control, speakers exhibit lasting priming effects. In both participant groups, a similar magnitude of structural priming was observed with lags of two vs. four intervening sentences; no decay of priming was evident across conditions. Given that lasting priming effects have been attributed to implicit learning mechanisms in healthy adults (Bock et al., 2007; Bock & Griffin, 2000; Chang et al., 2006; Dell & Chang, 2014; Hartsuiker et al., 2008), these results suggest that implicit language learning abilities may be spared in aphasic speakers as well. These findings are consistent with a previous report of cumulative structural priming in aphasic speakers (Saffran & Martin, 1997), and with the finding that aphasic individuals show successful implicit learning of auditory word sequences (Schuchard & Thompson, 2014) and artificial grammar (Schuchard & Thompson, under review). However, further research is needed to fully understand implicit language learning abilities in agrammatic aphasia given that mixed findings have been reported in the literature (cf. (Christiansen et al., 2010; Zimmerer et al., 2014). However, the existence of intact structural priming effects in agrammatic speakers, as demonstrated in the present study and others (Cho & Thompson, 2010; Hartsuiker & Kolk, 1998; Marin & Schwartz, 1998; Saffran & Martin, 1997), suggests that the sentence production system of these individuals retains the ability to adapt to linguistic input.

We now turn to the relationship between the magnitude of structural priming and the degree of linguistic impairments. On the basis of implicit learning accounts of structural priming (e.g., Chang et al., 2006; Dell & Chang, 2014), we predicted that speakers with more severe language impairments (agrammatic speakers vs. controls, agrammatic speakers with greater vs. lesser aphasia severity) would exhibit larger priming effects, reflecting increased error-based learning (i.e., an inverse preference effect). Broadly consistent with this prediction, a previous study by Hartsuiker & Kolk (1998) reported structural priming effects for aphasic speakers even under experimental conditions in which controls did not show them, indicating more reliable structural priming in agrammatic as compared to control speakers. However, in that study, the control participants showed little implicit structural priming;

reliable priming was seen only when participants were explicitly instructed to reuse the prime structure. Given that numerous studies of healthy speakers have reported reliable implicit priming effects (Pickering & Ferreira, 2008), the limited priming effects for control speakers in Hartsuiker and Kolk (1998)'s study make the comparison with agrammatic speakers difficult to interpret. In the present study, we found mixed evidence for a relationship between priming effects and linguistic impairments. The results of both Experiments 1 and 2 did not indicate a greater magnitude of priming in agrammatic speakers as compared to controls. The absence of an inverse preference effect at the group level may relate to the inclusion of several participants with mild agrammatism, who performed within the normal range on the priming task (although not on language testing measures), as well as the selection of a relatively simple sentence type (datives compared to passives) and a task which minimized lexical retrieval demands, which likely supported sentence production in agrammatic speakers. However, follow up analyses showed that speakers with more severe aphasia showed larger priming effects. This latter finding is consistent with the proposal that structural priming effects reflect error-based implicit learning, and are thus enhanced in populations with language impairments (Anderson & Conture, 2004; Tsiamtsiouris & Cairns, 2009). However, the relation between priming effects and language impairments requires further study using structures that are more substantially impaired in agrammatic speakers (e.g., passives vs. actives; see e.g., Cho & Thompson, 2010; Hartsuiker & Kolk, 1998), which may provide a stronger test of this relationship. In addition, online measures such as speech-onset latencies may provide a more sensitive measure of priming effects and their relationship to linguistic deficits. For example, two previous studies reported greater priming effects, as measured by speech-onset latencies, in speakers who stutter vs. those who do not (Anderson & Conture, 2004; Tsiamtsiouris & Cairns, 2009). In one study (Anderson & Conture, 2004), priming effects were evident in speech-onset latencies but not in offline production patterns.

Several aspects of the present findings are potentially relevant for the design of language treatment programs for sentence production deficits in agrammatic aphasia. First, consistent with grammatical encoding accounts of agrammatism, the results suggest that structural representations are intact in agrammatic aphasia, including syntactic representations as well as the mapping from thematic roles to syntactic structures. Thus, these findings provide empirical support for Treatment of Underlying Forms (Thompson & Shapiro, 2005) as well as Mapping Therapy for sentence production (Rochon, Laird, Bose, & Scofield, 2005), both of which focus on improving mapping from thematic roles to syntactic structures. Second, the present results suggest that structural priming may boost production of complex structures in agrammatic aphasia (cf. (Cho & Thompson, 2010; Hartsuiker & Kolk, 1998; Saffran & Martin, 1997)), and that such gains may be relatively long-lasting. Thus, it may be effective to incorporate structural priming paradigms into language treatment protocols. Third, the results demonstrate that individuals with more severe language impairments show larger priming effects and thus may particularly benefit from priming-based treatment protocols (cf. (Kohen, Kalinyak-Fliszar, & Martin, 2007)).

Conclusion

The present study used structural priming to examine sentence production processes in agrammatic aphasia and unimpaired control speakers. In both participant groups, significant priming was found for syntactic structures as well as the mapping between thematic roles and syntactic structures. Lasting structural priming effects (with up to four intervening trials) were also observed, with similar magnitudes across participant groups and conditions. Aphasic speakers with more severe language impairments showed larger priming effects, consistent with implicit learning accounts of structural priming. The results suggest that structural priming paradigms may build upon agrammatic speakers' intact linguistic representations and implicit learning ability, and therefore may prove useful as a means of treating sentence production deficits in agrammatism.

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Appendix

Appendix 1

Experimental target and prime sentences for the DO/PO conditions (shown in the DO structure), Experiment 1.

	Item	Stimuli
TARGET	1	The teacher is giving the class the test.
	2	The priest is giving the orphan the gift.
	3	The singer is handing the fan the guitar.
	4	The servant is handing the prince the crown.
	5	The barber is offering the boy the haircut.
	6	The retailer is offering the shopper the discount.
	7	The coach is passing the receiver the football.
	8	The waiter is passing the customer the bread.
	9	The agent is selling the athlete the insurance.
	10	The hunter is selling the pilot the gun.
	11	The cowboy is showing the visitor the ranch.
	12	The sailor is showing the friend the boat.
PRIME	1	The committee is awarding the researcher the grant.
	2	The lawyer is bringing the partner the document.
	3	The writer is assigning the editor the novel.
	4	The instructor is promising the student the equipment.
	5	The curator is lending the assistant the relic.
	6	The senator is assigning the advisor the policy.
	7	The client is bringing the specialist the funds.
	8	The artist is lending the patron the painting.

Item	Stimuli
9	The architect is sending the engineer the blueprint.
10	The board is awarding the reporter the honor.
11	The vendor is promising the manager the linen.
12	The widow is sending the daughter the money.

Appendix 2

Experimental target (shown in the DO structure) and prime sentences for the provide-animate/ provide-inanimate conditions, Experiment 1.

	Item	Stimuli
TARGET	1	The mother is giving the infant the toy.
	2	The officer is giving the driver the ticket.
	3	The carpenter is handing the cousin the hammer.
	4	The speaker is handing the audience the note.
	5	The host is offering the guest the chicken.
	6	The bartender is offering the cheerleader the beer.
	7	The farmer is passing the neighbor the apple.
	8	The director is passing the actor the script.
	9	The salesman is selling the scholar the computer.
	10	The lady is selling the bride the gown.
	11	The girl is showing the guardian the uniform.
	12	The nurse is showing the doctor the chart.
PRIME	1	The critic is crediting the chef/restaurant with the dessert.
	2	The mayor is providing the minister/chapel with the donations.
	3	The dean is presenting the professor/college with the trophy.
	4	The governor is burdening the commander/foundation with the project.
	5	The man is providing the patient/firm with the invoice.
	6	The chairman is trusting the secretary/enterprise with the proposal.
	7	The general is crediting the soldier/bureau with the prize.
	8	The landlord is supplying the tenant/apartment with the water.
	9	The employer is supplying the staff/office with the cabinets.
	10	The judge is burdening the clerk/court with the case.
	11	The actress is trusting the jeweler/store with the necklace.
	12	The designer is presenting the model/auction with the dress.

Appendix 3

Experimental target and prime sentences for Lag 2 (shown in the DO structure), Experiment 2.

	Item	Stimuli
TARGET	1	The captain is giving the pirate the treasure.

	Item	Stimuli
	2	The uncle is giving the nephew the bicycle.
	3	The mentor is handing the traveller the compass.
	4	The journalist is handing the publisher the article.
	5	The analyst is offering the chief the formula.
	6	The broker is offering the investor the bonds.
	7	The technician is passing the boxer the glove.
	8	The dealer is passing the player the card.
	9	The butcher is selling the worker the steak.
	10	The cook is selling the operator the salad.
	11	The musician is showing the orchestra the violin.
	12	The pupil is showing the tutor the homework.
PRIME	1	The detective is serving the suspect the soda.
	2	The florist is throwing the husband the bouquet.
	3	The trainer is buying the runner the shoes.
	4	The crew is serving the beverage to the passenger.
	5	The dentist is teaching the helper the procedure.
	6	The aunt is baking the youngster the turkey.
	7	The pitcher is throwing the catcher the baseball.
	8	The accountant is teaching the banker the lesson.
	9	The woman is baking the plumber the cookie.
	10	The nanny is feeding the toddler the oatmeal.
	11	The preacher is feeding the homeless the soup.
	12	The sponsor is buying the refugee the blanket.

Appendix 4

Experimental target and prime sentences for Lag 4 (shown in the DO structure), Experiment 2.

	Item	Stimuli
TARGET	1	The surgeon is giving the baby the medicine.
	2	The gardener is giving the housewife the tomato.
	3	The deputy is handing the president the agenda.
	4	The referee is handing the wrestler the towel.
	5	The scientist is offering the panel the evidence.
	6	The attorney is offering the thief the settlement.
	7	The dancer is passing the colleague the outfit.
	8	The tourist is passing the doorman the luggage.
	9	The mechanic is selling the builder the gadget.
	10	The merchant is selling the gentleman the sweater.
	11	The inventor is showing the niece the telescope.
	12	The collector is showing the family the antique.

	Item	Stimuli
PRIME	1	The attendant is serving the golfer the peanut.
	2	The postman is throwing the resident the parcel.
	3	The composer is buying the performer the piano.
	4	The maid is serving the leader the cocktail.
	5	The jockey is teaching the horse the trick.
	6	The sister is baking the roommate the muffin.
	7	The columnist is throwing the novice the newspaper.
	8	The historian is teaching the teenager the concept.
	9	The wife is baking the consultant the potato.
	10	The spy is feeding the agency the data.
	11	The owner is feeding the pet the snack.
	12	The associate is buying the boss the cigar.

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Highlights

- Two experiments examined structural priming in aphasic and unimpaired speakers.
- Both groups exhibited structural priming and thematic priming.
- Both groups exhibited lasting structural priming (2-4 intervening sentences).
- Greater aphasia severity was associated with larger priming effects.

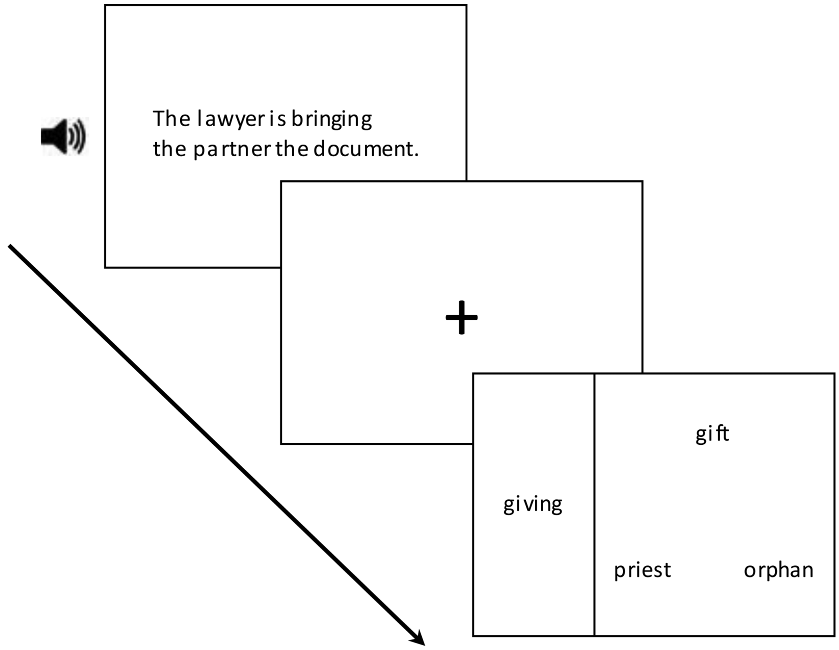

Figure 1.
An experimental trial for Experiment 1 (DO prime).

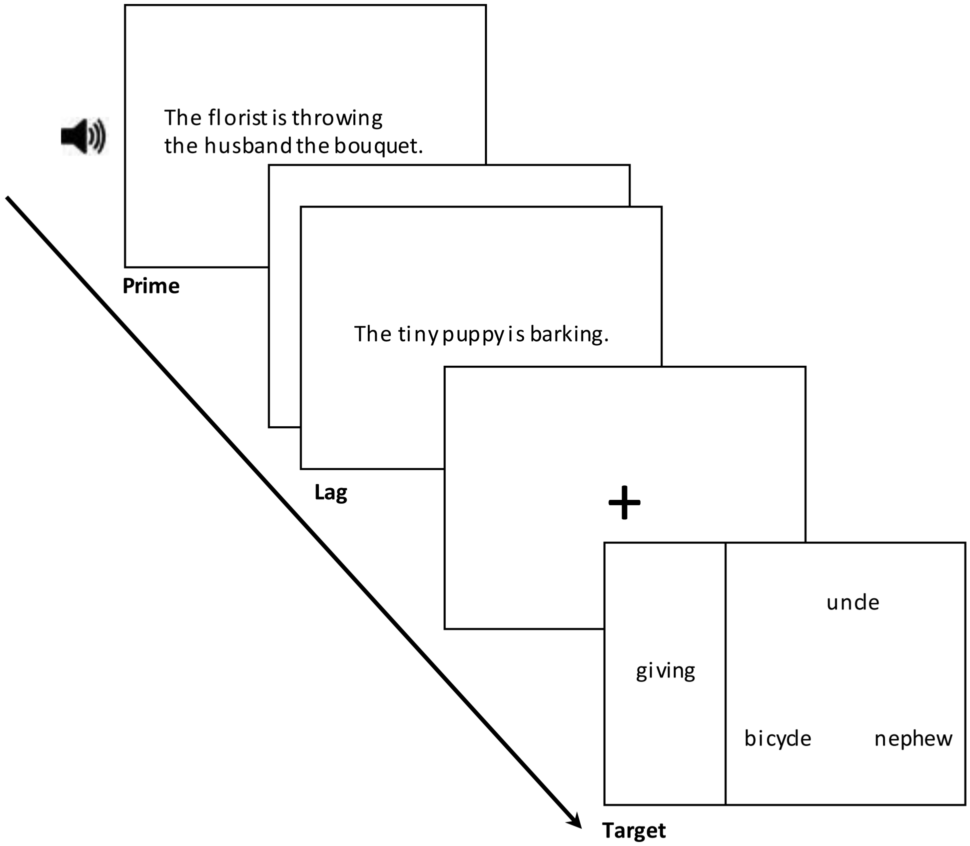

Figure 2.
An experimental trial for Experiment 2 (Lag 2, DO prime).

Table 1

Agrammatic participants' language test scores.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	M (SD)
Western Aphasia Battery-R (WAB-R)														
AQ (max 100)	74.3	74.8	76.8	71.7	77.6	75.2	89.6	88	78	87.8	83	82.8	85.4	80.4 (6)
F (max 10)	5	5	4	4	5	5	5	6	5	6	5	5	6	5.1 (0.6)
AC (max 10)	7.5	8.9	9.1	8.5	7.8	8	10	9.8	7.9	9.6	9.8	10	9.7	9.0 (0.9)
R (max 10)	8.4	7.2	8.1	5.1	9.4	7	10	9.2	7.6	10	8.8	8.3	9	8.3 (1.4)
N (max 10)	8.3	8.3	8.2	9.3	7.6	8.6	9.8	9	8.5	9.3	8.9	9.1	9	8.8 (0.6)
Northwestern Assessment of Verbs and Sentences (NAVS)														
Verb Naming Test (VNT)														
1-arg	60	100	100	100	80	80	100	80	100	100	100	100	100	92 (13)
2-arg	70	100	100	100	90	100	100	70	100	100	90	90	80	92 (11)
3-arg	43	86	86	100	71	100	71	57	71	86	71	86	43	75 (19)
Verb Comprehension Test (VCT)														
1-arg	100	100	100	100	80	100	100	100	100	100	100	100	100	98 (6)
2-arg	100	100	100	100	100	100	100	100	100	100	100	100	100	100 (0)
3-arg	86	100	100	100	100	100	100	100	100	100	100	100	100	99 (4)
Argument Structure Production Test (ASPT)														
1-arg	100	100	100	100	100	100	100	100	100	100	100	100	100	100 (0)
2-arg	100	87	100	100	100	100	100	100	100	100	100	100	93	98 (4)
3-arg	67	75	75	58	67	58	92	83	83	92	83	92	92	78 (13)
Sentence Production Test (SPPT)														
C	100	93	80	33	53	87	100	87	NA	100	93	100	87	84 (21)
NC	27	67	53	0	20	0	100	53	NA	87	67	47	60	48 (32)
Sentence Comprehension Test (SCT)														
C	87	100	53	87	53	73	100	93	60	100	87	93	87	83 (17)
NC	53	80	60	80	67	20	87	80	73	100	73	53	67	69 (20)

Note: Unless indicated, values provided are percent correct. AQ = Aphasia Quotient; F = Fluency; AC = Auditory Comprehension; R = Repetition; N = Naming; 1-arg = one-argument verb; 2-arg = two-argument verb; 3-arg = three-argument verb; C = Canonical; NC = Noncanonical

Table 2

Accuracy (proportion of correct dative responses out of all responses), proportion of DO responses (out of all correct dative responses), and magnitude of priming effects (subtraction of proportion of DO responses across conditions), for control and agrammatic participants, by prime type, Experiment 1.

Accuracy					
Group	**PO**	**DO**	**Provide-animate**	**Provide-inanimate**	**Overall**
Control	0.97 (0.05)	0.95 (0.07)	0.97 (0.04)	0.97 (0.06)	0.97 (0.04)
Agrammatic	0.87 (0.11)	0.85 (0.13)	0.87 (0.16)	0.85 (0.16)	0.86 (0.11)

Proportion of DO responses					
Group	**PO**	**DO**	**Provide-animate**	**Provide-inanimate**	**Overall**
Control	0.32 (0.20)	0.59 (0.16)	0.61 (0.21)	0.54 (0.23)	0.52 (0.23)
Agrammatic	0.17 (0.14)	0.38 (0.24)	0.29 (0.27)	0.29 (0.17)	0.28 (0.22)

Magnitude of priming effects			
Group	**Structural (DO - PO)**	**Thematic-animate (Provide-animate - PO)**	**Thematic- inanimate (Provide-inanimate - PO)**
Control	0.27 (0.17)	0.29 (0.20)	0.22 (0.15)
Agrammatic	0.21 (0.22)	0.12 (0.21)	0.12 (0.12)

Note: Means (standard deviations) are provided. PO = prepositional object; DO = double object.

Table 3

Parameters of mixed-effects regression models of priming effects, Experiment 1.

	Estimate	Std. Error	*t*-value	*p*-value
Priming Effects: Control Group				
Intercept	0.108	0.239	0.452	0.651
Prime Type: DO vs. PO	1.221	0.261	4.675	<0.001
Prime Type: Provide-animate vs. PO	1.370	0.282	4.853	<0.001
Prime Type: Provide-inanimate vs. PO	1.097	0.295	3.725	<0.001
Prime Type: Provide-animate vs. DO	0.150	0.272	0.550	0.582
Prime Type: Provide-inanimate vs. DO	−0.123	0.294	−0.419	0.675
Prime Type: Provide-inanimate vs. Provide-animate	−0.273	0.272	−1.004	0.315
Priming Effects: Agrammatic Group				
Intercept	−1.177	0.305	−3.857	<0.001
Prime Type: DO vs. PO	1.138	0.341	3.337	<0.001
Prime Type: Provide-animate vs. PO	0.418	0.413	1.014	0.311
Prime Type: Provide-inanimate vs. PO	0.739	0.341	2.165	0.030
Prime Type: Provide-animate vs. DO	−0.720	0.357	−2.019	0.043
Prime Type: Provide-inanimate vs. DO	−0.399	0.302	−1.323	0.186
Prime Type: Provide-inanimate vs. Provide-animate	0.321	0.392	0.819	0.413
Priming Effects: Control and Agrammatic Groups				
Intercept	−0.519	0.189	−2.744	0.006
Group: Agrammatic vs. Control	−1.275	0.379	−3.366	<0.001
Prime Type: DO vs. PO (Syntactic)	1.196	0.204	5.869	<0.001
Prime Type: Provide-animate vs. PO (Thematic-animate)	0.950	0.228	4.159	<0.001
Prime Type: Provide-inanimate vs. PO (Thematic-inanimate)	0.849	0.211	4.028	<0.001
Group (Agrammatic vs. Control) × Prime Type: DO vs. PO (Syntactic)	−0.098	0.409	−0.239	0.811
Group (Agrammatic vs. Control) × Prime Type: Provide-animate vs. PO (Thematic-animate)	−0.937	0.472	−1.986	0.047
Group (Agrammatic vs. Control) × Prime Type: Provide-inanimate vs. PO (Thematic-inanimate)	−0.408	0.426	−0.959	0.337

Table 4

Accuracy (proportion of correct dative responses out of all responses), proportion of DO responses (out of all correct dative responses), and magnitude of priming effects (subtraction of proportion of DO responses across conditions), by prime type, Experiment 2.

Accuracy					
Group	**Lag 2-PO**	**Lag 2-DO**	**Lag 4-PO**	**Lag 4-DO**	**Overall**
Control	0.93 (0.05)	0.96 (0.06)	0.96 (0.06)	0.97 (0.04)	0.96 (0.04)
Agrammatic	0.82 (0.15)	0.86 (0.15)	0.85 (0.13)	0.85 (0.16)	0.84 (0.13)

Rate of DO responses					
Group	**Lag 2-PO**	**Lag 2-DO**	**Lag 4-PO**	**Lag 4-DO**	**Overall**
Control	0.37 (0.19)	0.57 (0.16)	0.40 (0.14)	0.61 (0.15)	0.49 (0.19)
Agrammatic	0.23 (0.16)	0.39 (0.16)	0.19 (0.14)	0.37 (0.19)	0.29 (0.18)

Magnitude of priming effects (Rate of DO responses across conditions)		
Group	**Lag 2 (DO – PO)**	**Lag 4 (DO – PO)**
Control	0.20 (0.20)	0.20 (0.14)
Agrammatic	0.16 (0.14)	0.17 (0.12)

Note: Means (standard deviations) are provided. DO = double object; PO = prepositional object.

Table 5

Parameters of mixed-effects regression models of priming effects, Experiment 2.

	Estimate	Std. Error	*t*-value	*p*-value
Priming Effects: Control Group				
Intercept	−0.054	0.154	−0.351	0.725
Prime Type: DO vs. PO	0.842	0.173	4.879	<0.001
Lag: Lag 4 vs. Lag 2	0.148	0.174	0.851	0.395
Prime Type (DO vs. PO) × Lag (Lag 4 vs. Lag2)	0.025	0.348	0.071	0.944
Priming Effects: Aphasic Group				
Intercept	−1.060	0.235	−4.510	<0.001
Prime Type: DO vs. PO	0.906	0.238	3.810	<0.001
Lag: Lag 4 vs. Lag 2	−0.243	0.233	−1.045	0.296
Prime Type (DO vs. PO) × Lag (Lag 4 vs. Lag2)	0.228	0.456	0.500	0.617
Priming Effects: Control and Agrammatic Groups				
(Intercept)	−0.538	0.133	−4.053	<0.001
Prime Type: DO vs. PO	0.842	0.138	6.117	<0.001
Lag: Lag 4 vs. Lag 2	−0.016	0.137	−0.118	0.906
Group (Agrammatic vs. Control)	−0.967	0.265	−3.652	<0.001
Prime Type (DO vs. PO) × Lag (Lag 4 vs. Lag 2)	0.073	0.274	0.267	0.790
Prime Type (DO vs. PO) × Group (Agrammatic vs. Control)	−0.011	0.276	−0.040	0.968
Lag (Lag 4 vs. Lag 2) × Group (Agrammatic vs. Control)	−0.329	0.273	−1.206	0.228
Prime Type (DO vs. PO) × Lag (Lag 4 vs. Lag 2) × Group (Agrammatic vs. Control)	0.080	0.547	0.147	0.883