Language recovery in aphasia following implicit structural priming training: a case study

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Abstract

Background & Aims: Individuals with aphasia show difficulty producing sentences as a result of impaired syntactic production. Studies of structural priming in healthy speakers show that long-term learning of syntactic structures can occur via experience-based implicit adaptation in the production system. Structural priming facilitates sentence production in individuals with aphasia; however, it remains unknown if structural priming can be used as a treatment paradigm targeting longer-term language recovery in aphasia. The current study examined the feasibility and efficacy of implicit structural priming treatment in an individual with agrammatic aphasia.

Methods & Procedures: MJ received a total of 12 sessions of implicit structural priming training. We measured production of trained and untrained prepositional dative sentences on daily probes, maintenance of the treatment effects at 4-weeks post-training, and training-induced changes in the production of connected speech samples (Cinderella, WAB-R picture description).

Results: MJ showed significant improvement in producing both trained and untrained prepositional dative sentences over training sessions. Importantly, these effects were maintained at a 4-week follow-up without intervention. Notable improvement was also seen in syntactic complexity of connected speech production such as increased production of lexical verbs and sentences.

Conclusions: These findings suggest that it is feasible to use implicit structural priming as a treatment paradigm to target syntactic production in aphasia and that implicit structural priming may result in long-term global language recovery in agrammatic aphasia via experience-based strengthening of connections between linguistic representations.

Introduction

Many individuals with agrammatic aphasia show difficulty grammatically encoding a message into a sentence structure, resulting in reduced syntactic complexity. While the precise nature of the deficit is still being explored, it is generally agreed that agrammatic sentence production is a result of abnormal 'processing' of representational units during the message-structure mapping, rather than loss of specific linguistic representations (Bastiaanse & Zonneveld, 2004; Linebarger, Schwartz, & Saffran, 1983; Linebarger, Schwartz, Romania, Kohn, & Stephens, 2000; Linebarger, Schwartz, & Kohn, 2001, Saffran, Schwartz, & Marin, 1980; Lee & Thompson, 2011a; 2011b; Lee, Yoshida, & Thompson, 2015). For example, even when they produce word-order errors or omit obligatory arguments in sentences, these individuals show relatively preserved sensitivity to grammatical constraints in grammaticality judgment tasks and in on-line measures such as eyetracking (Thompson & Choy, 2009; Lee & Thompson, 2011a; 2011b; Linebarger et al., 1983; Shapiro, Gordon, Hack, & Killackey, 1993). Their speech accuracy or onset latencies are improved when provided with sentence primes (Hartsuiker & Kolk, 1998; Saffran & Martin, 1997) or verb primes that share the same argument structure with the target sentence (Lee et al., 2015), suggesting that the additional support can compensate for their reduced activation and processing of linguistic information.

Despite the pervasiveness of the deficit, only a few theoretically-based treatment approaches are available to improve sentence production in aphasia. The primary focus of these treatment approaches is to establish 're-mapping' of meaning to sentence structure through explicit training of various linguistic rules (e.g., Thompson, Shapiro, Kiran, & Sobecks, 2003; Thompson & Shapiro, 2005; Rochon, Laird, Bose, & Scofield, 2005; Schwartz, Saffran, Fink, Meyers, & Martin, 1994). For example, in the Treatment of Underlying Forms (TUF), the

individual with aphasia is trained to comprehend and produce the verb and the thematic roles of its arguments (e.g., agent, theme, etc.) in canonical sentence forms and then to arrange various sentence constituents to form the targeted non-canonical sentence structures such as object relative clauses (e.g., 'Pete saw the bride who the groom was carrying'). Similarly in Mapping Therapy, the participant is asked to identify the arguments' thematic roles (e.g., agent, theme etc.) in relation to the main verb in order to improve mapping between meaning and sentence structure through explicit learning of the thematic roles of the verb arguments (Rochon et al., 2005; Schwartz et al. 1994). These treatment approaches have yielded reliable acquisition of trained stimuli in many individuals with aphasia who underwent the treatments. Although not unequivocal, some maintenance and generalization of the treatment gains were observed (Man, Dick, & Lee, 2015).

Different from the 'explicit' learning underlying most current language treatments in aphasia, a rapidly growing body of literature on structural priming suggests that long-term learning of syntactic structures occurs implicitly, i.e., without explicit recognition of the grammatical rules. Structural priming is a speaker's tendency to echo syntactic structures from recent experience (Bock, 1986). The phenomenon of structural priming is most commonly studied using sentences with syntactic alternations such as dative and active/passive alternations. For example, a speaker is more likely to produce a prepositional dative (PD) structure (e.g., 'the boy is giving the guitar to the singer') after being exposed to a PD prime (e.g., 'the girl is throwing the bone to the dog') rather than the dative objective (DO) counterpart (i.e., 'the boy is giving the singer the guitar'). The speakers' tendency to re-use the same structures persists despite changes in the meaning, in the lexical heads (e.g., verbs) used between primes and targets, and even across languages, indicating that the priming is associated with the abstract

linking between the messages and syntactic configurations in the grammar, rather than utterance- or content-specific repetition (Bock, 1986; Bock & Loebell, 1990; Hartsuiker & Kolk, 1998; Hartsuiker, Pickering, & Veltkamp, 2004; Pickering & Branigan, 1998; Potter & Lombardi, 1998).

Structural priming has been viewed to reflect a process of error-based implicit language learning throughout a lifespan (Bock & Griffon, 2000; Bock, Dell, Chang, & Onishi, 2007; Branigan, Pickering, Steward, & McLean, 2000; Chang, Dell, Bock, & Griffin, 2000; Chang, Dell, & Bock, 2006; see Pickering & Ferreira, 2008 for different accounts of structural priming). A language user makes predictions on how the sentence structure will unfold as he/she hears or produces the prime. If the prediction is incorrect (e.g., the DO structure was predicted but the PO prime was heard), this prediction error leads to weight changes in the system so that the primed structure (e.g., NP V NP PP) is more expected in the future (e.g., Chang et al., 2000; 2006). This experience-based strengthening in the speaker's knowledge on how certain relational structures in the message (e.g., Agent-Theme-Goal) are expressed in a certain sentence structure (e.g., NP V NP PP) results in implicit, long-term language learning. In line with this proposal, studies show that no specific instruction on sentence structures or word order is necessary for the priming effects to manifest (Bock & Griffin, 2000; Hartsuiker & Kolk, 1998). The magnitude and presence of priming effects do not change as a function of input modality (simply listening to the primes vs. repeating the primes, Bock et al., 2007) or whether participants could remember the primes or not (Bock, Loebell, & Morey, 1992). Patients with anterograde amnesia show normal priming effects, indicating that structural priming is independent of explicit memory processes (Ferreira, Bock, Wilson, & Cohen, 2008). Importantly, the priming effects persist over interrupting fillers, particularly when no lexical heads (e.g., verbs) are shared between the primes

and targets (Bock, 1989, Bock & Griffin, 2000; Bock et al., 2007; Branigan & McLean, 2016; Kaschak & Borreggine, 2008). Lastly, the priming effects are greater for less frequent structures or less proficient speakers because of their greater prediction error-based weight changes (Hartsuiker & Kolk, 1998; Hartsuiker, Kolk, & Huiskamp, 1999; Cho-Reyes, Mack, & Thompson, 2016).

Some studies have examined cumulative, lasting, learning effects of structural priming (Savage, Lieven, Theakston, & Tomasello, 2006, Kaschak, Kutta, & Schatschneider, 2011; Shin & Christianson, 2012). Savage et al. (2006) showed that processing five passive (prime) sentences with different verbs caused 4-year-old children to produce more passives 30 days later, if the children had an opportunity to produce the primes one week after the original priming session. In a study with Korean adult learners of English, Shin & Christianson (2012) compared effects of different priming paradigms on long-term learning of double-object datives and separated phrasal-verb constructions involving a post-object particle. Only the group of participants who received the implicit structural priming (no lexical overlap, 4-5 interrupting fillers, and no explicit instructions) continued to produce more target sentences 1-day later. The groups who received explicit priming (same verbs between the primes and targets, no interrupting fillers) and implicit priming with explicit instructions on the sentence structures did show immediate priming effects but not the maintenance effects at post-testing.

Emerging evidence shows that structural priming can facilitate production of various syntactic structures that are otherwise difficult to produce in individuals with aphasia, including transitive (actives/passives), datives (PD/DO) (Hartsuiker & Kolk, 1998; Saffran & Martin, 1997; Yan, Martin, & Slevc, 2015), and clitic pronouns (Rossi, 2015). For example, Saffran and Martin (1997) examined structural priming effects on production of transitive and dative

structures in five persons with varying types of aphasia. Participants described pictures after repeating transitive (actives, passives) or dative (PD, DO) primes. Priming was found for transitive structures, but not for dative structures. However, after the priming procedure, the participants produced more dative structures in a sentence elicitation task compared to before priming. Hartsuiker and Kolk (1998) examined production of transitive and dative sentences in 12 persons with Broca's aphasia and 12 controls under three different conditions: participants repeated prime sentences (a) to perform a sentence memory task, (b) to describe pictures without a memory task, and (c) to reuse the same structure of the prime sentence. While the controls showed priming only in the explicit condition (c), the aphasic participants showed similar priming effects regardless of instruction type, indicating that these priming effects were automatic rather than strategic. Additionally, structural priming effects are shown across languages in individuals with bilingual aphasia (Verreyt, Bogaerts, Cop, Bernolet, De Letter, Hemelsoet, Santens, & Duyck, 2013) and can last up to 4 interrupting sentences in a group of agrammatic speakers (Cho-Reyes, Mack, & Thompson, 2016), indicating that implicit learning of sentence structures remains intact in this population.

These findings suggest that there is potential for structural priming to be used as a training paradigm targeting long-term improvement of syntactic production in persons with aphasia. Additionally, the lack of reliance on explicit memory processes during implicit structural priming may benefit individuals whose explicit short-term memory or other attention-based cognitive control interferes with re-learning of grammatical rules. Martin and colleagues, using structural priming treatment, found that structural priming could facilitate accessibility of syntactic structures in individuals with aphasia and the improvement was maintained up to 5 months (Kohen, Kalinyak-Fliszar, & Martin, 2007; Benetello, Kohen, Kalinyak-Fliszar, & Martin, 2012;

Kalinyak-Fliszar, Kohen, Benetello, & Martin, 2013). However, they focused on the participant's ability to orally 'repeat' the target structures and the clinician provided feedback on correct repetition of the sentence structures during treatment sessions; thus, it remains unclear if structural priming training can result in improved production in self-generated sentences and if their results are truly due to implicit learning of syntactic structures.

The purpose of the current study was to shed light on the mechanisms of sentence production deficits and recovery in aphasia by investigating the efficacy and feasibility of using implicit structural priming training in a participant with agrammatic aphasia. Using a single subject design, our participant with agrammatic aphasia (MJ) was trained to produce sentences with prepositional dative (PD) structure following an implicit structural priming paradigm. To ensure that the implicit syntactic learning was the core mechanism of the training-induced improvement, our structural priming training used different lexical heads (verbs as well as nouns) between primes and targets, a relatively long-lag (4 fillers) between primes and target, and no explicit instructions or feedback on the sentence structure (Shin & Christianson, 2012; Griffin & Bock, 2000; Bock et al., 2007). Specifically, we asked whether repeated exposure to the PD structure via structural priming can result in (a) cumulative learning of trained and untrained sentences in daily probes over time, (b) maintenance of the gains at 4-weeks post-training, and (c) generalized improvement in connected speech production. It was hypothesized that if structural priming occurs via longer-term adaptation in cognitive processes associated with syntactic production, our implicit structural priming training should result in long-term global language recovery. Thus, we expected to observe successful acquisition of the trained as well as untrained sentences over time, maintenance of the training effects, and improved syntactic complexity in connected speech.

Methods

Participant

MJ was a 57-year-old female who suffered from a left hemispheric ischemic stroke encompassing the left frontal, parietal, and occipital lobes 3 years prior to study participation. MJ received 12 years of education and was a homemaker. MJ was a monolingual native speaker of English with corrected-to-normal hearing and vision and no known history of speech-language disorders or neurological or psychological disorders prior to her stroke. MJ had not received any speech therapy since one year post onset of her stroke. This study was approved by the Purdue University's Institutional Review Board and informed consent was obtained from MJ prior to the study.

Table 1 shows MJ's performance on the Western Aphasia Battery-Revised (WAB-R, Kertesz, 2006) and the Northwestern Assessment of Verbs and Sentences (NAVS, Thompson, 2011) at baseline. MJ exhibited moderate Broca's aphasia (WAB-R AQ = 60.4). While her auditory comprehension was relatively preserved for daily conversations, her verbal expression was characterized by halting and telegraphic speech, consisting of mostly single-word utterances and mild motor speech difficulties. On the NAVS, MJ's auditory comprehension of verbs and sentences was better than production of verbs and sentences. At the single verb level, she showed intact comprehension of verbs (100%), but reduced production of verbs (73%) with the greatest errors occurring with dative verbs (29%) compared to transitive (90%) and intransitive verbs (100%). On the Argument Structure Production subtest, in which she was asked to construct sentences given an action picture (e.g., a boy tickling a girl) and written words (boy, tickle, girl), she performed at 69% accuracy, with greater errors in dative sentences (42%) compared to transitive (80%) and intransitive (100%) sentences. On the Sentence Production Priming subtest

(SPPT), in which she was asked to describe pictures with sentences following the clinician's sentence prime, she produced canonical sentences at 7% accuracy and noncanonical sentences at 0% accuracy. The errors were dominated by strings of words without a grammatical sentence structure (e.g., "girl wagon boy" for 'the girl is pulling the boy'; "Pete cat and dog" for 'Pete saw the cat who was biting the dog').

Table 1. MJ's performance on language tests

Test	Baseline	Post-training
Western Aphasia Battery -Revised		
Information content (10)	7	9
Fluency (10)	4	5
Auditory Comprehension (10)	7.8	7.9
Naming (10)	7.6	7.5
Repetition (10)	3.8	4.3
Aphasia Quotient (100)	60.4	67.4
Northwestern Assessment of Verbs and Sentences		
Verb Naming Test (n=22)	73%	77%
Verb Comprehension Test (n=22)	100%	100%
Argument Structure Production Test (n=32)	69%	97%
Sentence Priming Production Test (n=30)	7%	13%
Sentence Comprehension Test (n=30)	63%	50%

An analysis of MJ's connected speech samples (WAB-R picture description and Cinderella story retell) revealed that the majority of MJ's productions in the WAB picnic picture description task consisted of strings of nouns (18 total nouns), similar to her errors on the NAVS. She produced only 1 sentence (i.e., "man um catching fish"). Her speech was characterized by slowed and effortful productions (29 words per minute), and less than half of her description

contained informative content (% CIUs=46%). MJ's performance on the Cinderella story re-tell task was similar. Approximately half of her re-telling of Cinderella contained informative content (% CIUs=52%) with 23 words per minute produced. The majority of her productions consisted of strings of nouns (31 total nouns), with 5 verbs and 3 sentences. Only 2 sentences with correct argument structure were produced (e.g., "And then 'inderella sweeping").

Stimuli

For the target sentence stimuli, a total of 10 imageable dative verbs (e.g., 'give', 'throw') and 60 animate and inanimate nouns were prepared to create 10 trained and 10 untrained stimuli. Some verbs were used more than once with different nouns in the sentences. Different verbs and nouns were used between the trained (e.g., 'the boy is giving a guitar to the singer') and untrained (e.g., 'the teacher is teaching the math to the student') target sentences. The nouns were no more than 2 syllables in length and the verbs ranged from 1 to 3 syllables with the mean length matched between the trained and untrained sentences (Nouns: M (SD) = 1.53 (.51) vs. 1.4 (.50), t (58) = 1.03, p = .31; verbs: M (SD) = 1.4 (.89) vs. 1 (0), t (8) = 1.00, p = .35). For both nouns and verbs, their log lemma frequencies were also matched between trained and untrained stimuli (Nouns: M (SD) = 1.96 (.92) vs. 2.30 (.68), t (58) = -1.61, p =.11; verbs: M (SD) = 2.36 (.55) vs. 2.40 (.35), t (8) =-.157, p = .88; Center for Lexical Information database [CELEX]; Baayen, Piepenbrock, & van Rijn, 1993). For both trained and untrained sentences, their black-and-white line drawings were prepared. The picture stimuli were normed on 20 college students and only the pictures that elicited 80% of the target dative (PD or DO) sentences were included in the study. The stimuli elicited PD sentences 68% of the time and DO sentences 32% of the time. Given more frequent use of the PD structure in the healthy speakers, the PD structure (as opposed to the DO structure) was chosen as the target sentence structure for the training task. A

different set of 10 dative verbs (each verb repeated twice) and 60 nouns was used to create 20 written prime sentences (e.g., ‘the owner is renting a boat to the customer’). Two prime sentences were paired with each trained target stimulus, resulting in a total of 10 prime-target pairs in training. There was no semantic or phonological overlap in the nouns and verbs used between the primes and the target.

Additionally, 40 filler sentences were prepared to create a lag between the presentation of the prime and the target. The fillers included structures that are unrelated to the PD structure, including sentences with an adjective predicate (e.g., ‘the bus is late’), a locative predicate (e.g., ‘the book is on the table'), and a subject noun with an adjectival modifier (e.g., ‘the yellow purse is mine’), similar to previous structural priming studies (Bock & Griffin, 2000; Bock et al., 2007).

Design & Procedure

A single subject multiple baseline design was used, consisting of baseline sessions, training sessions with daily probes, and a 4-week follow-up session. Baseline sessions consisted of a set of language tests (WAB-R, NAVS), the Cinderella story re-telling task, and the probes of trained and untrained target sentences. These same measures were obtained post-training. At the 4-week follow-up, a probe was conducted for the trained and untrained sentences to assess maintenance effects.

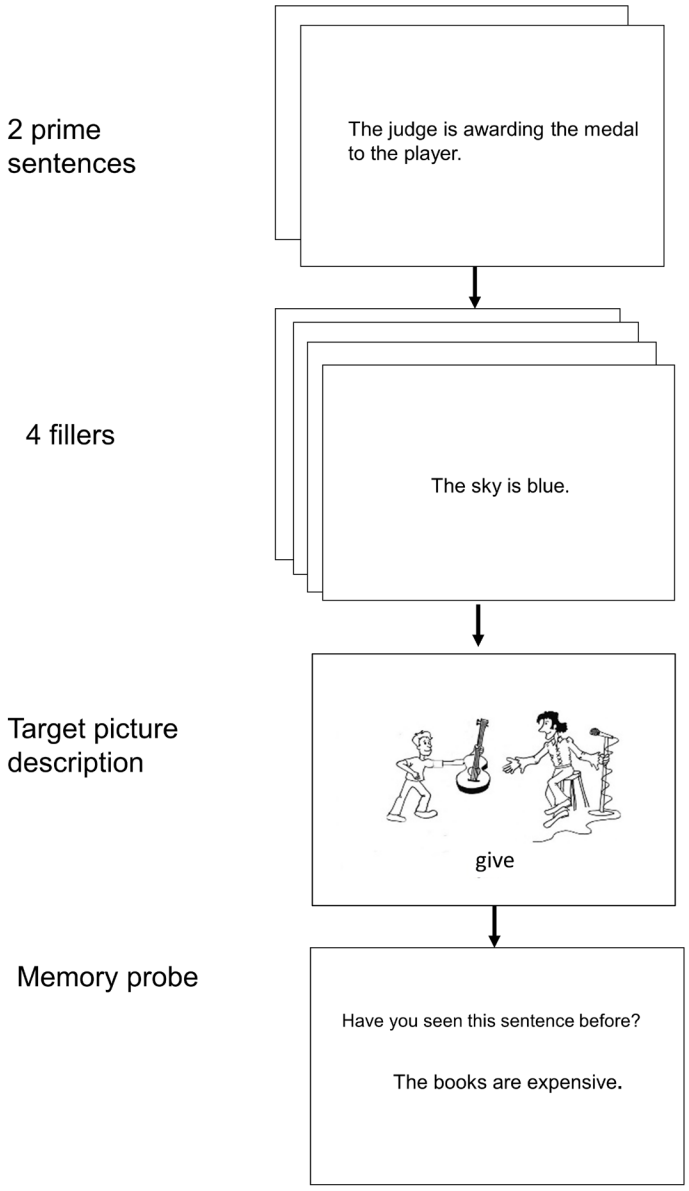
Each training session consisted of a familiarization task for single nouns and verbs, a daily probe of the trained and untrained target stimuli, and the structural priming training. During the familiarization task, MJ was ‘familiarized’ with the target nouns and verbs as singletons in order to ensure that her word-finding deficits would not interfere with the priming effects during training. MJ was asked to name each character or object or action in a confrontational naming

task. MJ was provided with the appropriate target word when she produced incorrect responses. During the daily probe, MJ's production of the trained and untrained target stimuli without priming sentences or any clinician feedback was assessed. MJ was presented with the trained and untrained target pictures and asked to describe what was happening in the picture using a sentence. No written or verbal support was provided for the lexical items (nouns or verbs), and only neutral feedback (e.g., "You're doing fine") was provided during the probe. The first daily probe was conducted after the first training session; thus, the probe data for each session reflected the gains obtained from the previous training session.

The training task was developed based on the implicit structural priming paradigms used in previous studies (Bock & Griffin, 2000; Bock et al., 2007, Shin & Christianson, 2012), in which different verbs and multiple interrupting fillers were used between the primes and target. In addition, the structural priming task was disguised as a sentence recognition task. MJ was informed that she would practice reading and remembering sentences, and making sentences using pictures. No explicit instruction regarding the sentence structures was provided. Figure 1 shows a sample trial during the structural priming training session. For each trial, MJ was first visually presented with 2 prime sentences, which she read aloud after the clinician's model. The primes were then followed by 4 filler sentences, which MJ read aloud again. The target picture was then presented with the target verb written at the bottom of the picture. MJ was asked to "describe what is happening in the picture using a single sentence". After the target picture description, a sentence recognition (memory) probe was presented, in which MJ had to indicate whether she had previously seen the sentence by saying yes or no. Feedback was provided only during oral reading of the prime and filler sentences with regard to the accuracy of reading individual words (e.g., correcting phonological errors). No feedback was provided regarding the

accuracy of sentence structure during oral reading of the primes or the picture description to ensure that any changes during the training was attributable to the implicit processing of prime structures. Each training trial was repeated twice during the training session in a randomized order, resulting in a total of 20 training trials.

Figure 1. A sample trial for the structural priming training



The training was administered 3 times a week by the second author with each session lasting 90 minutes (30 minutes for familiarization and probe and 60 minutes for training). All training materials were presented via MacBook Pro laptop, using Experimental Builder (SR Research), which automatically recorded MJ's speech responses into a wave file. MJ's responses were transcribed on-line and checked for reliability after each training session. The criteria to terminate the training were either after the completion of 15 sessions total or 90% accuracy on daily probes over 3 consecutive sessions. MJ met the latter criteria, ending the training after 12 sessions.

Data Analyses

MJ's responses during the probes and follow-up testing were scored for accuracy. The response was considered 'correct', if it included all target words in the PD structure (e.g., 'the boy is giving the guitar to the singer')[1]. Semantically related words (e.g., 'boy' for 'man'; 'hand' for 'give'), omission of copulas (e.g., 'is'), substitution of semantically appropriate prepositions (i.e., 'for the boy' instead of 'to the boy'), and intelligible sound errors (e.g., " 'livery" for 'delivery') were accepted. When MJ attempted multiple sentential responses for a trial, the last response was scored (e.g., "the chef is taking..no..ok, <u>the chef is serving the chicken to the king</u>"). A response was considered a sentential response when at least a subject noun and a lexical verb was produced.

MJ's errors on daily probes were tallied by type: non-sentence responses, argument structure errors, verb substitution, and noun errors. The non-sentence responses included when MJ produced a string of nouns without a verb (e.g., "um…man…gun…and um…judge"). The argument structure errors included sentence responses with incorrect argument structure ("man

[1] Although the target pictures allowed production of both PD and DO sentences, MJ did not produce any DO sentences in all training and probe sessions.

giving guitar the singer" for 'the man is giving guitar to the singer'), those with a missing argument (e.g., "the postman delivering the man"), and those with incorrect order of arguments (e.g., "the man is showing the dress to the woman" for 'the woman is showing the dress to the man'). The verb substitution errors were when MJ produced a non-dative verb, producing a legitimate, but non-dative sentence structure (e.g., "boy holding microphone" for 'the boy is giving a guitar to the singer (with a microphone)'; "pizza livery…woman… go get change" for 'the man is delivering pizza to the woman'). The noun errors included responses with non-target noun substitution (e.g., "the postman is writing the ticket to the girl" for 'the policeman is writing the ticket to the girl').

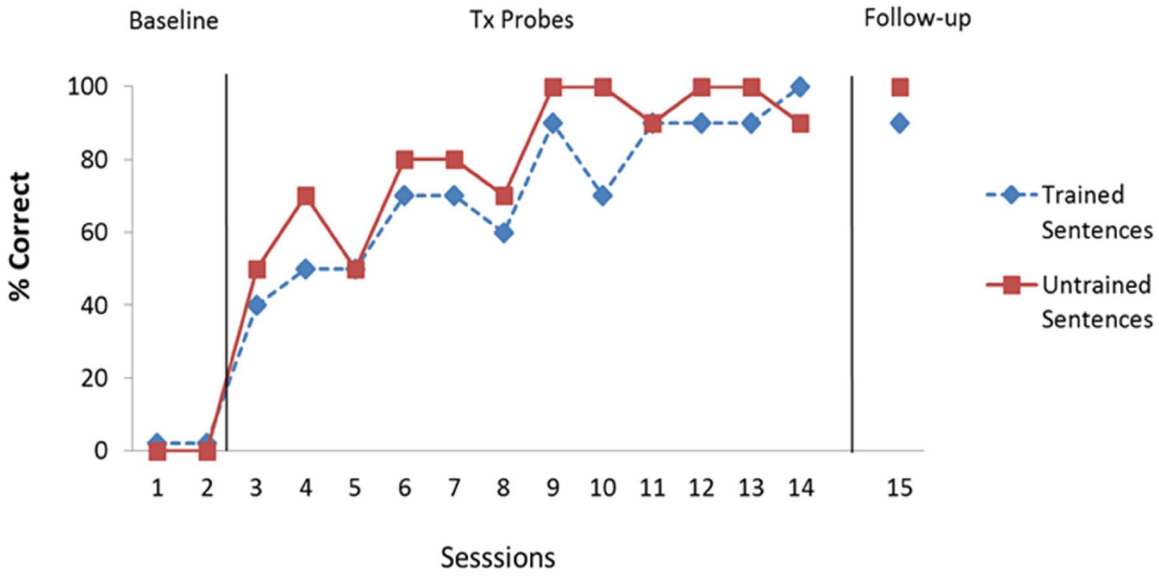
For the analysis of narrative speech, MJ's speech samples from the WAB-R picture description and story re-telling (Cinderella) were transcribed verbatim. A set of measures was computed following previous studies (Nicholas & Brookshire, 1993; Saffran, Berndt, & Schwartz, 1989), including percent production of correct information units (% CIU, Nicholas & Brookshire, 1993), and words per minute. The number of 'sentences' was counted based on the utterances that included at least a subject noun and a main verb including but not limited to utterances of noun+main verb, noun+copula+adjective, and noun+copula+prepositional phrase (Saffran, Berndt, & Schwartz, 1989). Among the sentences produced, the number of sentences with correct argument structure was tallied separately following the criteria used in previous studies (Kim & Thompson, 2000; Cho-Reyes & Thompson, 2012). For example, "Cinderella is cleaning the house' constituted as a sentence with correct argument structure, while "Cinderella dancing the prince" would be considered a sentence with incorrect argument structure.

Results

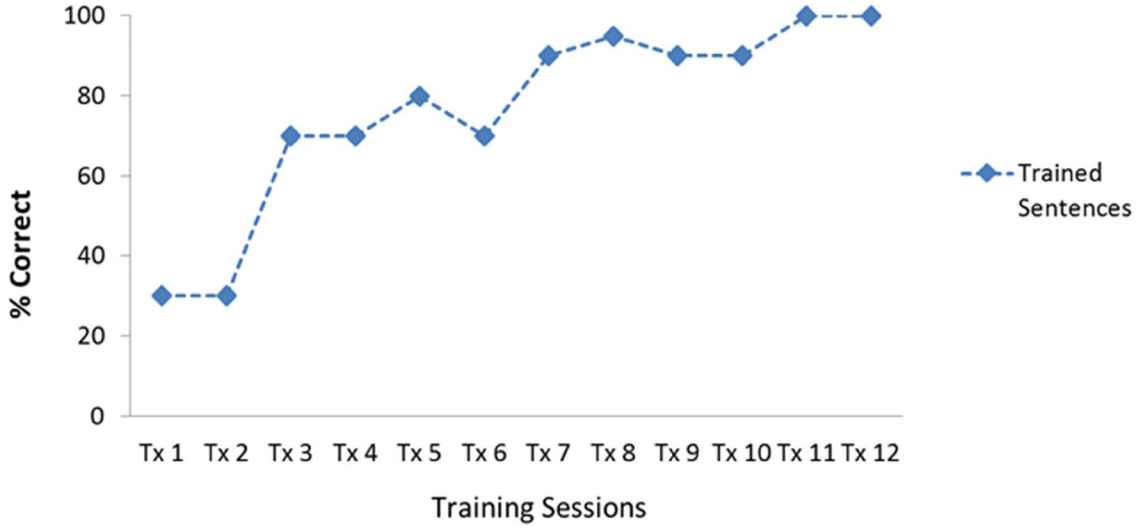
Acquisition of trained and untrained sentences: Figure 2 shows the changes in MJ's performance on the daily probe measures where she produced sentences independently (without the preceding prime sentences or written verbs) (Figure 2a) as well as during the priming training sessions, where she produced target trained sentences following sentence primes (Figure 2b). At baseline, MJ correctly produced 0% of both trained and untrained sentences in two probes consecutively, indicating inability to produce the target structure independently. During the priming sessions, MJ showed steady improvement in producing the trained PD target sentences, indicating that the structural priming paradigm was effective in facilitating immediate production of the target structure in MJ (Figure 2b). The parallel improvement was reflected in daily probes for both trained and untrained stimuli (Figure 2a). After the first session of priming training, her accuracy increased to 40% and 50% for the trained and untrained stimuli, respectively. Then, MJ showed steady improvement for both trained and untrained PD structures over the course of training. She achieved 90% accuracy for the trained sentences in 3 consecutive sessions at the 12 treatment sessions. Parallel improvement was shown for MJ's production of the untrained sentences, resulting in 100% accuracy post-training. McNemar's exact tests revealed that MJ's scores at post-training were significantly greater than MJ's baseline performance for both trained (p = .004) and untrained sentences (p = .002).

Figure 2. MJ's performance on daily probes over different phases of training (a) and on structural priming training sessions (b)

a.



b.



Maintenance effects: A follow-up probe was taken at 4-weeks post-training. As shown in Figure 2, MJ continued to show 90% accuracy for the trained and 100% for the untrained sentences, indicating that she maintained training-induced improvements in her sentence production.

Error analysis: The results of error analysis are shown in Table 2. The most frequent error produced during baseline was a non-sentence error, in which MJ produced a string of words (e.g., "painting, picture, uh man…yeah" for 'the artist is showing the picture to the man'). As the training began, the number of non-sentence errors was substantially reduced and MJ's errors were dominated by argument structure errors and verb substitutions. At the end of the training, MJ still produced (very few) noun errors but no structural errors.

Table 2. Error analysis by type for daily probes

	Baseline		Training Probes												Follow-up
Error type \ Probe #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Non-Sentence	14	7	2	1	1	0	2	0	0	0	0	0	0	0	0
Argument Structure	1	9	5	5	7	4	1	5	0	1	2	1	0	0	0
Verb substitution	4	4	4	2	1	1	1	1	1	0	0	0	0	0	0
Noun errors	1	0	0	0	0	0	0	1	0	2	0	0	1	1	1
Total (Max:20)	20	20	11	8	9	5	4	7	1	3	2	1	1	1	1

Generalization to connected speech: As shown in Table 3, an analysis of the connected speech samples pre- vs. post-training revealed positive changes in the measures of % CIUs and the numbers of verbs, sentences, and sentences with correct argument structures. On the WAB-R picnic picture description task, her % CIUs increased from 46% to 66%. MJ produced a larger number of verbs (3 to 11) and sentences (1 to 12), with an increase in the number of sentences with correct argument structure (1 to 10). On the Cinderella story, % CIUs increased from 52%

to 69%. She showed improved production in the number of verbs (5 to 10), sentences (3 to 11), and sentences with correct argument structure (2 to 6). The changes in the noun production and speech rate (word per minute) were not consistent. She produced 20 (vs. 18) and 40 (vs. 31) nouns in the WAB-R picture description and Cinderella story post vs. pre-training. The WPM was slightly decreased in the WAB-R picture description (29 to 25) but increased (23 to 28) for the Cinderella story.

Table 3. An analysis of MJ's connected speech samples pre vs. post-training

Narrative speech production task	Baseline	Post-training
WAB-R picture description		
WPM	29	25
% CIU	46%	66%
# of nouns	18	20
# of verbs	3	11
# of sentences	1	12
# of sentences with correct argument structure	1	10
Cinderella story re-tell		
WPM	23	28
% CIU	52%	69%
# of nouns	31	40
# of verbs	5	10
# of sentences	3	11
# of sentences with correct argument structure	2	6

Changes in language tests: Although not one of our measures of interests, MJ showed some positive changes on the WAB and NAVS post training (see Table 1). On the WAB-R (Kertesz, 2006), MJ showed a 7 point clinically significant improvement on the aphasia severity rating; WAB-AQ score increased from 60.4 to 67.4 at the end of the training (Katz & Wertz, 1997). The greatest improvement was shown in the Spontaneous Speech section (from 11 to 14; see above for detailed results of connected speech analysis). On the NAVS (Thompson, 2011), M.J. showed improvement on the Argument Structure Production subtest from 69% to 97%, reflecting improved ability to produce sentences following training. Only a limited change (7% to 13%) was observed in the scores on the Sentence Production Priming Test (SPPT), a subtest for production of canonical (actives, subject-relative clauses, and subject wh-questions) and noncanonical (passives, object relative clauses, and object wh-questions) sentences. Although MJ failed to produce the various target syntactic structures on the SPPT, it was noted that she produced increased number of transitive sentences with correct argument structure (e.g., 'the man is saving the girl' for 'the girl was saved by the man' or 'Pete saw the girl who the man was saving') post-training, compared to her dominant production of non-sentential utterances pre-training (e.g., "Pete dog and cat" for 'Pete saw the cat who was biting the dog').

Discussion

Previous studies have suggested that structural priming has potential for language treatment in aphasia based on the findings that individuals with aphasia are more likely to produce relatively complex target structures (e.g., passives and dative structures) given structural primes. However, no study has yet examined whether the implicit structural priming can actually lead to longer-term improvement in language production in these individuals. This study examined the feasibility and efficacy of using structural priming as a language treatment in one

individual with moderate agrammatic aphasia (MJ). We measured training-induced cumulative improvement on the production of trained and untrained PD structures on daily probes, maintenance effects at a 4-week follow-up, and changes in connected speech production (WAB picture description and Cinderella story re-tell) pre- vs. post-training. Within the error-based implicit learning account of structural priming, it was hypothesized that the structural priming training would result in longer-term global changes in MJ's language production via experience-based adaptations in the syntactic production system (Chang et al., 2000; 2006).

MJ showed notable improvements in all measures of interest, in line with our hypothesis. On daily probes, where MJ described the trained and untrained target pictures without primes, MJ was not able to produce any dative sentences at baseline. However, only after 1 session of structural priming training, MJ's production of PD sentences improved to 40% for trained and 50% for untrained sentences, joining the previous studies showing intact priming effects in speakers with aphasia (Cho-Reyes et al., 2016; Hartsuiker & Kolk, 1998; Saffran & Martin, 1997; Rossi, 2015; Verreyt et al., 2013). More importantly, MJ continued to show steady improvement over the training in priming sessions as well as on daily probes, eventually producing 90-100% consistently towards the end of training. These findings suggest that she was able to apply the learned syntactic structure from the priming sessions to an independent sentence production context. In turn, they suggest that structural priming not only improved MJ's sentence production by temporarily increasing the probability of activating the target structure (Hartsuiker & Kolk, 1998), but also facilitated cumulative learning of abstract syntactic structures over time (Branigan & McLean, 2016).

The most significant finding of the current study is that MJ continued to produce the trained and untrained sentences successfully 1-month post-training without intervention. To our

knowledge, this is the first evidence showing long-term maintenance effects of implicit structural priming in aphasia. Long-term learning from structural priming has been shown in 4-year-old children at 1-month (Savage et al., 2006) and 1-day after priming in Korean adult learners of English (Shin & Christianson, 2012). For persons with aphasia, the longest persistence effects of structural priming on sentence production were at one-week later in the study by Saffran and Martin (1997). In their study, although their five participants with aphasia did not show priming effects for dative sentences during the priming session, they reliably produced more dative sentences at post-priming sessions. On the other hand, the participants showed successful priming effects for passive sentences but they failed to show increased production of passives at post-training sessions. In addition, their post-priming sessions were conducted at varying time points (from 1-hour to 1-week later) across participants. Thus, it is difficult to know how reliably the long-term learning effects can be attributed to priming effects and how many of their participants showed the priming effects 1-week later. Although still preliminary, the current data suggest that structural priming can be used as a treatment targeting long-term language recovery in aphasia and they underscore the power of structural priming as an implicit learning mechanism.

The results of the error analyses also mirror the priming-induced strengthening in MJ's syntactic production. Her initial errors were dominated by strings of words in the absence of any sentence structure (e.g., "man, uh, uh,…paint, man" for 'the artist is showing the picture to the man'), indicating her reduced ability to access syntactic representations. However, after initial structural priming sessions, MJ produced more sentence-level errors, including verb substitutions (e.g., "boy is holding microphone") and sentences with incorrect argument structures (e.g., "the artist is showing the man", "man giving guitar the singer"). At the end of the training, the only

residual errors were noun substitutions (e.g., “the postman is writing a ticket for the girl” instead of ‘the policeman is writing a ticket for the girl’). A similar change was observed in the errors that MJ produced on the SPPT subtest of the NAVS post-training. Her sentential errors emerged, although they were not the target sentences. These changes reflect that increased availability of syntactic representations allowed MJ to arrange nouns more successfully into sentence structures over the course of training.

One ultimate goal of language treatments in aphasia is to facilitate recovery in daily conversations outside of the therapy sessions. If the structural priming training indeed resulted in long-term adaption in the cognitive processes underlying the sentence production system, MJ should show improvement in her ability to produce sentences in connected speech. Notable generalization effects were shown in MJ’s connected speech samples. Specifically, increased syntactic complexity was noted post-training in both WAB-R picture description and Cinderella story re-tell. MJ produced more sentences post-training as well as sentences with correct argument structures, although these sentences were mostly intransitive and transitive sentences. In addition, she also produced increased lexical verbs in both narrative tasks. Given that the filler sentences included copula verbs only (e.g., ‘the sky is blue’, “the blue notebook is mine”), these changes are difficult to attribute to MJ’s repeated exposure to filler sentences. The lack of reliable improvement in speech fluency (WPM) and noun retrieval (the number of nouns produced) further suggests that the changes were specific to MJ’s improved syntactic processing post-training. Although the precise mechanisms of this generalization is open to further investigation, increased accessibility of the PD structure following priming training might have facilitated activation of the simpler syntactic structures, including transitive (NP V NP) and intransitive (NP V) structures and the corresponding verb lemmas (Pickering & Branigan, 1998;

Pickering & Ferreira, 2008). Together, the results in connected speech production suggest that the implicit structural priming training can lead to global language recovery that supports syntactic production in various contexts.

The current findings also provide insight into syntactic learning in agrammatic aphasia. While most existing treatment approaches focus on explicit training of syntactic operations for generating sentences (e.g., Thompson & Shapiro, 2005; Rochon et al., 2005), this study shows that implicit learning of grammatical rules remains intact and can yield positive treatment outcomes in agrammatic aphasia (see also Schuchard & Thompson, 2014 for evidence of successful implicit word sequence learning in aphasia; cf. Christiaanson, Kelly, Shillcock, & Greenfield, 2010; Zimmerer, Cowell, & Varley, 2014). That is, the sentence production system of aphasic individuals may retain the ability to adapt to structural input without relying on conscious (re)learning of grammatical rules (Cho-Reyes et al., 2016; Hartsuiker & Kolk, 1998; Saffran & Martin, 1997) and the effect of the adaptation can be long-lasting and generalize to different language production contexts. Although the current results need to be replicated in more individuals with aphasia, it is possible that implicit-learning based treatment approaches may be more beneficial for the individuals who demonstrate limited learning due to their explicit memory deficits.

Further investigation is clearly needed to delineate the critical factors that could contribute to the substantial implicit syntactic learning observed in the current study. Individual factors might influence the outcomes. For example, MJ's severity in language impairment, more specifically near complete inability to produce dative sentences prior to treatment might have boosted the priming effects as a result of exaggerated error-based weight changes over repeated priming sessions (Chang et al., 2006; Cho-Reyes et al., 2016). Schuchard, Nerantzini, and

Thompson (2016) reported that repeated passive exposure to grammatically correct passive sentences and matching pictures did not lead to improved comprehension of passive sentences in persons with agrammatic aphasia, although the same individuals showed positive implicit sequence learning in a visuo-motor serial reaction time task. Thus, obligating production (or some sort of active processing) of the target syntactic forms may be a critical factor to consider in designing sentence production (and comprehension) treatments using implicit structural priming.

In conclusion, the current study examined whether structural priming can be used as a treatment paradigm targeting long-term cumulative syntactic learning in agrammatic aphasia. It was shown that the implicit structural priming training resulted in improved production of trained and untrained target sentences over time, maintenance of the improvement 4-weeks later, and increased syntactic complexity in connected speech samples. Thus, the findings of our case study show that it is feasible to use structural priming as a treatment targeting long-term global language recovery in aphasia and that structural priming facilitates implicit-learning of syntactic structures via experience-based strengthening of connections between linguistic representations.

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