Effect of lexical accessibility on syntactic production in aphasia: An eyetracking study

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ABSTRACT

Purpose. Healthy speakers use both word-level and structure-level information to ease sentence production processes. Structural priming facilitates message-structure mapping in aphasia. However, it remains unclear if and how word-level information affects off-line and on-line sentence production in persons with aphasia (PWA). This eyetracking-while-speaking study examined the effect of lexical priming on production of syntactic (active/passive) structures in PWA.

Method. Eleven PWA and twenty healthy older adults (HOA) described transitive actions (*woman pulling horse*) following lexical priming, wherein the relative ease of lexical retrieval for the Agent or Theme was manipulated via an auditory probe (*what is happening with the woman/horse?*). It was examined whether or not PWA produce the sentence structure that allows earlier production of the primed word (e.g., passives when Theme was primed). Participants' eye fixation times to each character (Agent, Theme) were also monitored to examine if PWA show priming-induced preferential looks to one character from the earliest stage of production, consistent with word-driven planning.

Results. HOA showed increased production of passives over actives in the Theme vs. Agent prime condition. In eye fixation data, HOA showed priming-induced Theme advantage from the earliest time window (picture onset-400 milliseconds). PWA also showed a significant priming effect in off-line sentence production, with this priming effect being greater for the individuals whose syntactic processing is better preserved. In eye fixation data, however, PWA showed preferential fixations to the primed character at a later stage of sentence planning (400-800 milliseconds), following equal fixation time to Agent and Theme during the earliest time window.

Conclusion. HOA showed word-driven production in both off-line and real-time (eye fixations) production. Lexical accessibility effectively drove off-line syntactic production in PWA, especially for those whose syntactic capacity remains relatively preserved. However, PWA showed advanced processing of both characters in earliest eye fixation data, suggesting that successful word-driven off-line syntactic production was associated with atypical real-time sentence planning in aphasia.

INTRODUCTION

Sentence production requires intricate coordination of retrieving individual elements and putting them into the correct sentence structure. Deficits in message-to-sentence encoding are common in persons with aphasia (PWA) and across different aphasia types, significantly limiting their quality of life (Edwards & Bastiaanse, 1998; Faroqi-Shah & Thompson, 2004; McAllister, Bachrach, Waters, Michaud, & Caplan, 2009). For example, sentences with non-canonical word order such as passives, are often impaired in both fluent and non-fluent aphasias compared to sentences with canonical word order such as actives (Faroqi-Shah & Thompson, 2004; Edwards & Bastiaanse, 1998). Research to date has mostly focused on describing the causes of such deficits, attributing them to 'deleted' syntactic representations (Friedmann & Grodzinsky, 1997), faulty grammatical encoding processes (Bastiaanse & van Zonneveld, 2004; 2005; Lee, Yoshida, & Thompson, 2015; Thompson, Faroqi-Shah, & Lee, 2015) or reductions in general processing resources (Kolk, 1995; Linebarger et al., 2000). However, relatively little is known about how sentence production actually unfolds and what information effectively 'drives' the message-structure mapping processes in PWA. The present study addresses this knowledge gap by examining the effect of lexical accessibility on off-line and on-line (eyetracking) syntactic production in aphasia.

Language production proceeds incrementally. It is well-established that unimpaired speakers opportunistically use both relational (e.g., event-structural) and elemental (e.g., word-level) information to ease message-to-sentence encoding during incremental production (Bock, Irwin, & Davison, 2004; Ferreira & Bock, 2014 for review). Findings from structural priming studies have demonstrated that speakers tend to echo previously encountered message-structure mappings in future sentence production to facilitate information processing as part of implicit language learning

(Bock & Griffin, 2000; Branigan & McLean, 2016; Chang, Bock, & Dell, 2006; Jaeger & Snider, 2013; Pickering & Garrod, 2004; see Pickering & Ferreira, 2008 for review). For example, after hearing their conversational partner's use of a passive sentence, the speaker is more likely to produce a passive rather than an active structure to convey a similar message. Speakers' choices in syntactic structures are also affected by the relative ease or saliency in retrieving individual elements, resulting in production of the sentence structure that allows earlier production of the first accessible word (Bock, 1986; Bock & Warren, 1992; Gleitman, January, Nappa, & Trueswell, 2007; McDonald, Bock, & Kelly, 1993; Slevc, 2011). For example, speakers are likely to produce a passive structure (*the man is chased by the dog*) rather than an active structure (*the dog is chasing the man*) if the Theme '*man*' becomes available earlier than the Agent '*dog*'. This bias in word order production likely occurs when elements are easier to retrieve perceptually (e.g., increased visual attention) or linguistically (e.g., previously heard word).

Speakers' use of word- and structure-driven sentence planning strategies is also manifested in their eye movement patterns during language production (e.g., Bock et al., 2003; Gleitman et al., 2007; Griffin & Bock, 2000; Griffin, 2001; Lee & Thompson, 2011a, b; van de Velde, Meyer, Konokpa, 2014; see review in Ferreira & Bock, 2014). Previous studies have recorded eye movements while participants produced sentences describing simple action scenes or using written words, revealing that speakers tend to fixate at the depicted character or the word in the order of mention. Importantly, the processes of word- and structure-driven incremental planning are elucidated by distinctive eye fixation patterns occurring as early as 200-400 milliseconds from the picture onset, or the apprehension phase, revealing how speakers transform a non-linguistic message into language.

Theories of word-driven incremental planning hold that language production begins with element-by-element development of message material into the lexicon and sentence form. Encoding of the subject noun (and therefore, the rest of the sentence structure as well) is 'driven' by activation of a single character during the apprehension phase. When describing a two-character scene, a speaker's visual attention tends to be drawn to a more salient or 'primed' character within 400 milliseconds of picture onset, showing early preferential looks to the character. Then, the speaker would continue to encode it as the subject of the sentence, thereby retrieving its name, until they shift gaze to the next character at about 800 milliseconds from picture onset (Gleitman et al., 2007; van der Velde et al., 2014; Griffin, 2001).

Theories of structure-driven incremental planning, on the other hand, postulate that language production begins with a more holistic construal of message elements. When describing a transitive action scene, speakers direct their attention preferentially to one character to produce as the subject of the sentence only after apprehension of the event gist within 400 milliseconds. In this early time window, speakers do not yet fixate either character preferentially and these non-differentiated fixations to the characters in the scene have been suggested to reflect conceptual processing of multiple message elements and their 'aboutness' relations (Bock et al., 2003; Ferreira & Bock, 2014; Griffin & Bock, 2000; van de Velde et al., 2014). This encoding of rudiments of the utterance invokes the speaker's preferential fixation to the 'suitable' subject for upcoming lexicalization and sentence formulation.

Importantly, use of different production processes is not an intrinsic mechanism to a production system. Rather, speakers can flexibly use these production strategies in order to efficiently use processing resources during language production (Ferreria & Swets, 2002; Wagner et al., 2011; Lee et al., 2015). For example, in word-driven production, memory demands are

reduced because speakers do not have to 'buffer' linguistic materials before production. However, it assumes a certain degree of syntactic ability, because the speaker needs to flexibly build syntactic structures in response to varying activation levels of individual elements (deSmedt, 1990). On the other hand, structure-driven production may reduce demands for syntactic flexibility and/or lexical retrieval during speech, as it provides the speaker with a preview of the upcoming utterance; however, this may pose increased demands on pre-speech buffer.

Deficits in grammatical encoding processes are common in PWA. As of yet, little systematic research is available on whether both structural and word-level information facilitate the grammatical encoding processes in PWA and how individuals' syntactic ability is associated with the use of different sentence production strategies. Identifying the underlying mechanisms of successful sentence production in PWA will help to establish more effective treatment strategies to facilitate sentence production and identify the extent to which individuals' deficits should be considered when selecting intervention approaches. An increasing number of studies have reported that structural priming remains preserved, facilitating sentence production in PWA (e.g., Cho-Reyes, Mack, & Thompson, 2016; Hartsuiker & Kolk, 1998; Lee, Man, Ferreira, & Gruber, 2019; Man, Meehan, Martin, Branigan, & Lee, 2019; Yan, Martin, & Slevc, 2018; see Lee, Hosokawa, Meehan, Martin, & Branigan, 2019 for evidence in sentence comprehension). For example, PWA show increased production of rather complex sentences such as passives or double object datives after orally reading prime sentences (Cho-Reyes et al., 2016; Yan et al., 2018) or after simply hearing their interlocutor's use of the structures in a dialogue-like language game task (Man et al., in press; cf. Lee et al., 2019). In addition, there is evidence that structural priming effects are larger for PWA with greater syntactic deficits under certain conditions compared to those with relatively preserved syntactic ability, indicating that structure-driven production may be more effective for

some PWA (Cho-Reyes et al., 2016; see also Hartsuiker & Kolk, 1998; Lee, Yoshida, & Thompson, 2015).

However, it remains unclear whether word-level information can facilitate message-structure production in PWA and if so, how individual speakers' syntactic deficits are associated with use of word-driven sentence production. The purpose of the present study was to examine the effects of lexical priming on off-line and on-line syntactic production in PWA with the long-term goal of better delineating mechanisms of sentence production in aphasia. An eyetracking-while-speaking task was used in which participants described transitive action pictures following lexical priming for the Agent or Theme nouns. The relative ease of lexical retrieval, or lexical accessibility for the Agent or Theme participants of the event, was varied via an auditory prime probe of the word. Three questions were examined in the present study. The first question examined whether PWA demonstrate preserved ability to produce syntactically alternating (active/passive) structures, taking advantage of varying lexical accessibility. It was predicted that if word-level cues effectively guide grammatical encoding processes in PWA, they would produce the syntactic structure that allows earlier production of the primed word. For example, PWA would produce increased production of passive sentences over active sentences when the Theme noun is primed to be more accessible compared to when the Agent is lexically primed.

The second question examined the time course of the lexical priming effect by monitoring participants' eye fixations during sentence production. Specifically, it was asked whether PWA demonstrate use of word-driven incremental planning, as evidenced by priming-induced divergence in fixations to Agent and Theme characters from the earliest stage of sentence planning. Only a few eyetracking studies have examined real-time sentence production in PWA (Cho & Thompson, 2010; Lee & Thompson, 2011a; 2011b; Lee et al., 2015; Mack, Nerantzini, & Thompson, 2017).

Findings so far suggest that PWA tend to rely on structural planning to a greater extent than healthy speakers, although both planning strategies can be used by PWA. Lee and colleagues (2015) found that PWA produced sentences in a word-by-word manner when producing sentences in a fixed word order (e.g., *the clock and the pen are above the sofa*). However, they consistently showed evidence of advanced planning such as encoding the sentence's verb argument structure prior to speech onset when producing action-describing sentences (2011a; 2011b, 2015). Notably, this pattern was evident even when PWA did not differ from HOA in off-line production accuracy, indicating that PWA might engage in different real-time planning from HOA to successfully produce target sentences.

Mack et al. (2017) specifically examined treatment-induced changes in the early eye fixation patterns in individuals with agrammatic aphasia. Structural priming was used to elicit active and passive sentences in a group of HOA and PWA in the eyetracking picture description task. In addition, PWA received 12 weeks of Treatment of Underlying Forms (TUF; Thompson & Shapiro, 2005) to improve production of transitive sentences. The HOA showed no differential fixation patterns when producing active vs. passive sentences in the first 400 milliseconds from picture onset, followed by preferential fixations to the subject (Agent in actives and Theme in passives). This pattern of eye movements in HOA suggests that structural priming facilitates use of structure-driven planning (see van der Velde et al., 2014 for increased structural planning in young adults following cumulative structural priming). At pre-treatment, PWA directed fixations to one character within the initial 400 milliseconds and showed no clear evidence of divergent fixations for subject encoding after the 400 milliseconds. In addition, they produced very few passive sentences. At post-treatment, PWA showed significantly improved ability to produce passive sentences, and this

increased production was accompanied by non-differentiated fixations between Agent and Theme during the early apprehension phase, or structure-driven planning, as seen in HOA.

Given these existing studies, it is possible that PWA in the current experiment demonstrate qualitatively different eye fixation patterns from HOA in real-time, even when they show significant lexical priming effects on off-line choices of syntactic structures. It was predicted that if lexical priming facilitates use of word-driven planning in real-time, participants would show early divergence in fixations within 400 milliseconds from picture onset, dictating the rest of the linguistic formulation of the sentence. If our participants did not use word-driven planning in real-time, they would show no differential fixation patterns observed across the prime conditions during the apprehension phase and might demonstrate a later divergence in fixations to Agent and Theme.

Bearing on the issue of individual variability, the third question explored if there is any systematic relation between word-driven production and degrees of syntactic deficits in PWA. As mentioned above, word-driven production assumes some degree of syntactic ability since the speaker has to flexibly build syntactic structures in response to varying activation levels of individual words (deSmedt, 1990). Thus, it is possible that individual participants' syntactic processing ability modulates the degree of lexical priming effects on off-line and on-line sentence production. For example, lexical priming may be most effective to elicit production of different syntactic structures for individuals with relatively intact syntactic ability. Predictions for eye fixation patterns are less clear, as PWA may rely on either planning process to successfully produce syntactic structures in response to varying lexical accessibility. To address this exploratory question, it was examined whether or not individuals' scores on clinical tests of syntactic production and comprehension predict degrees of lexical priming effects on off-line syntactic production and early eye fixation patterns.

METHOD

Participants. A group of eleven participants with stroke-induced aphasia were tested (5 females, 6 males; age M (SD) = 69 (9.4), education M (SD) = 15.5 (4.5) years; post-onset since L CVA M (SD) = 47 (36) months). Twenty healthy older adults (HOA) were also tested (8 females, 12 males; age M (SD) = 71.2 (6.2), education = 16.8 (2.4) years). All participants passed a pure tone hearing screening at 500, 1000, 2000 Hz at 40 dB at least in one ear and reported normal or corrected-to-normal vision. They were monolingual native speakers of English. The Cognitive-Linguistic Quick Test (CLQT, Helm-Estabrooks, 2001) was administered to HOA to rule out the presence of any age-related cognitive-linguistic impairments. HOA scored an average of 3.99/4.0 on the Clinical Severity Rating (CSR) of the CLQT, indicating that they were within normal limits. Participants were compensated for their time and provided informed consent prior to the study.

For PWA, a set of language tests was administered (see Table 1). PWA presented with mild-to-moderate fluent or nonfluent aphasia based on the Western Aphasia Battery-Revised (WAB-R, Kertesz, 2006). Given that our priming task involved the use of auditory probes, we ensured that all PWA demonstrated relatively intact auditory comprehension of single words and simpler sentences, measured by the Auditory Comprehension section (8.8/10 or greater) of the WAB-R and the Verb Comprehension Test (82% or greater) and the Sentence Comprehension Test (60% or greater on canonical sentences) of the Northwestern Assessment of Verbs and Sentences (NAVS, Thompson, 2011). In addition, all PWA showed no more than mild-to-moderate deficits in naming of nouns and verbs, as measured by the Naming section (7.3/10 or higher) of the WAB-R and the Verb Naming Test (50% or higher) of the NAVS. PWA demonstrated at least 50% or higher accuracy on the Argument Structure Production Test

(ASPT) of the NAVS, indicating that the ability to formulate sentences (intransitive, transitive, and dative) in a structured test was somewhat preserved. They demonstrated more varied performance on the Sentence Priming Production and Sentence Comprehension Tests of the NAVS, with generally higher scores in the canonical sentences (actives, subject wh-questions, and subject relative clauses) compared to non-canonical sentences (passives, object wh-questions, object relative clauses).

Materials and Design. A total of 18 transitive sentences and their corresponding black-and-white line drawings were prepared. The stimuli were taken from previous studies, which effectively elicited both target (active or passive) structures as an effect of structural or lexical priming in young adults (Bock & Griffin, 2000; Griffin & Bock, 2000). The stimuli were also effective in eliciting target structures in HOA and PWA (Lee, Man, Ferreira, & Gruberg, 2019; Thompson, Dickey, Cho, & Lee, 2007). A majority of the stimuli (15/18) included events involving an animate theme (e.g., *a dog chasing a mailman*; *lightning striking a golfer*). It has been shown that the default preference for actives over passives is reduced when the patient of the action is animate (Bock et al., 1992; Ferreira, 1994; McDonald et al., 1993). The remaining three picture stimuli depicted events where both agent and theme were inanimate (e.g., *a truck is towing a car).* A set of 58 fillers were included consisting of intransitive (e.g., *a ball bouncing, a man laughing*) and dative (e.g., *the man is throwing a ball to the woman*) action pictures.

Two experimental lists were created. Each target picture was tested twice across the lists, once with the Agent primes and once with the Theme primes, yielding a total of 36 trials per participant (18/prime type). Within the list, each target picture was paired with only one prime type (e.g., Agent prime for list 1, Theme prime for list 2). The order of the experimental trials was pseudo-randomized such that at least 2 fillers intervened between transitive trials and no

Table 1. Language testing results for PWA.

	Western Aphasia Battery-Revised (WAB-R)					Northwestern Assessment of Verbs and Sentences (NAVS)						
PWA	AQ	Fluency	AC	Rep	Naming	VNT	VCT	ASPT	SPPT_C	SPPT_NC	SCT_C	SCT_NC
A01	77.5	5	9.1	8.1	8.7	86	100	91	87	47	100	100
A02	83.0	5	10.0	9.2	8.3	97	100	100	100	93	100	100
A03	87.0	9	9.8	9.8	7.9	68	86	97	100	87	87	93
A04	82.3	5	9.8	8.6	8.8	100	100	90	100	66	80	87
A05	69.6	5	8.7	4.4	7.7	73	100	100	13	0	93	27
A06	92.9	9	9.4	8.6	9.5	91	100	97	100	100	100	100
A07	74.3	4	8.4	8.4	7.4	79	82	53	60	40	60	60
A08	77.0	6	8.8	7.4	7.3	50	100	94	80	7	80	60
A09	96.2	9	10.0	9.4	9.7	100	100	100	100	100	100	100
A10	73.8	5	9.1	6.3	7.5	55	95	91	87	40	100	80
A11	85.0	8	9.3	9.5	6.7	95	100	100	93	80	80	73
Mean	81.7	6.4	9.3	8.2	8.1	81	97	92	84	60	89	80
SD	8.2	2.0	0.6	1.6	1.0	18	6	14	26	36	13	23

Note: AQ = Aphasia Quotient; AC = Auditory Comprehension; Rep = Repetition; VNT = Verb Naming Test; VCT = Verb Comprehension Test; ASPT = Argument Structure Production Test; SPPT_C= Sentence Priming Production Test _ Canonical; SPPT_NC = Sentence Priming Production Test _Noncanonical; SCT_C = Sentence Comprehension Test _Canonical; SCT_NC= Sentence Comprehension Test_Noncanonical

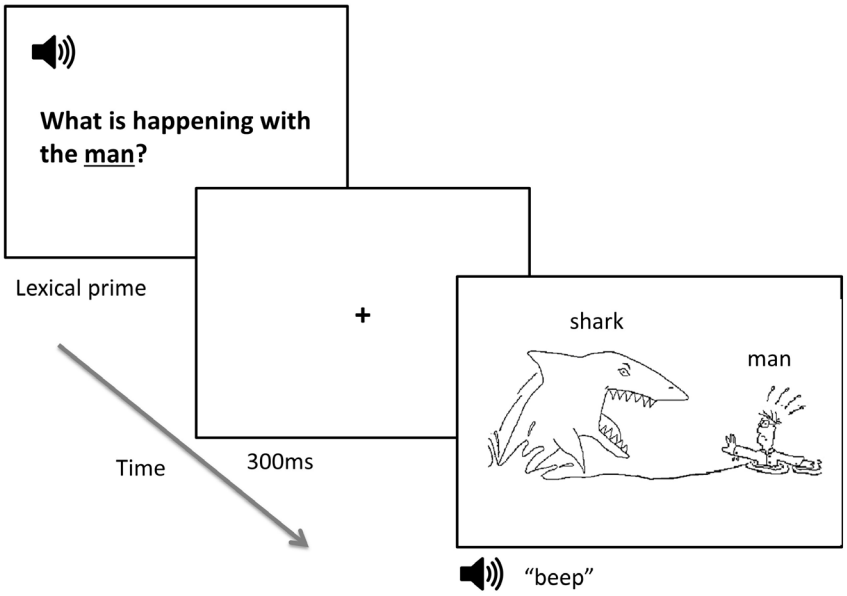
more than two trials were tested consecutively in the same prime condition. Each participant was tested on both lists across 2 sessions with at least 2 weeks in between sessions. The presentation order of the lists was counterbalanced across participants.

Procedure. An eyetracking picture description task in conjunction with auditory lexical priming was used. As demonstrated in Figure 1, the participant described a target picture using a sentence following an auditory priming probe. The relative accessibility of the Agent and Theme nouns was varied based on the 'givenness' of the nouns in the auditory probe sentence, similar to the procedure used in Slevc (2011). In order to prime for production of passive sentences, the participants heard the Theme (*man*) mentioned in the auditory probe (*what is happening with the man?*), whereas the Agent was mentioned in the probe to prime for active targets (*what is happening with the shark?*). For intransitive fillers, a neutral probe (*what's happening in the picture?)* was provided. For dative fillers, two nouns (either the agent and theme, or the agent and goal; e.g., *what is happening with the man and woman?*) were mentioned in the prime probe. Filler trials were also paired with an auditory prime to minimize strategic production of transitive targets in the participants. In order to minimize the influence of PWAs' word-finding deficits on the task, written words were provided on the picture stimuli (Figure 1). In addition, participants went through familiarization of the target nouns and verbs in singletons, using an oral reading task prior to the experiment.

During the experimental task, the participant was instructed to describe what is happening in the picture using a single sentence, and to try to start speaking as fast as they could. There were no specific instructions on what structures should be used in their responses. For each trial, an auditory prime was played through speakers followed by a fixation cross presented on the computer screen for 300 milliseconds. Then, the target picture was presented with a beep

sound (100ms) to indicate the onset of the picture stimulus, and the participant described the picture using a single sentence. Once they had completed describing the picture, the participant pressed the spacebar on the keyboard to advance to the next trial. For PWA, the experimenter controlled the keyboard to compensate for motor difficulties in some participants. Experimental Builder (SR research) was used to present stimuli on a 24-inch monitor and to record the participants' verbal responses. Participants' eye fixations were also recorded using an EyeLink 1000 Plus desktop remote monocular eyetracker (SR research, Ottawa, ON, Canada). The position and duration of the participants' eye fixations were sampled at a rate of 500 Hz. Participants' eye fixations were then aligned with their speech data to track when participants fixated to each character in the visual scene during sentence production. A set of 6 practice trials preceded the experimental items. No feedback on response accuracy was provided for experimental items.

Figure 1. A sample experimental trial. Production of a passive structure is primed by the auditory probe including the Theme noun ('man').



Data analysis.

Sentence production data. Sentence production accuracy was first obtained for each participant by computing proportions of 'correct' responses out of all responses. A response was considered as 'correct' if the response was either an active or passive structure. Substitutions of legitimate synonyms (e.g., *woman/girl; automobile/car; hit/strike*) and verb forms (e.g., *is striking/struck/strikes/strike* for actives), intelligible phonological errors, as well as within word self-corrections (e.g., *wo, no, man*) were accepted. For passives, the correct order of the Theme in the subject position and Agent in the post-verbal position and the use of the passive morphology (auxiliary + past participle of a verb + *by*) was required in order to be counted as 'correct'. When multiple attempts were made, the first sentential attempt was scored, defined minimally by the production of a subject noun phrase and verb phrase. For incorrect responses produced by PWA, their error types were tallied. The specific error types and examples are provided in Table 2. No error analysis was conducted for HOA due to their high accuracy in production. Each participant's data were coded by two trained coders with disagreements resolved by consensus.

The effect of lexical priming on participants' choices of syntactic (active or passive) structures was then analyzed based on 'correct' responses only. Each correct sentence response was binarized according to whether the participant produced a passive (1) or an active (0) structure. This binary variable was entered into statistical models (see the *Statistical analysis* section below). Given that only two alternating syntactic choices were possible for correct responses, it was tested if probability of producing an arbitrarily selected structure (passive structure in our case) would increase as an effect of different lexical (Theme, Agent) prime conditions. Thus, we compared proportions of passive responses over all correct (active +

passive) responses under the Agent vs. Theme prime conditions for each participant. A significant priming effect was reflected by an increased proportion of passive responses in the Theme, compared to the Agent prime condition.

Speech onset time data. Temporal boundaries of sentence regions were marked in Praat (Boersma & Weenik, 2016). For each response produced by a participant, the onset of the beep sound (indicating picture onset) and speech onset times of the subject and object nouns (*N1* and *N2*, respectively) were measured using acoustic and spectrogram analyses. These temporal boundaries were obtained to align with participants' eye fixation data to test our second research question on the time course of priming effects during real-time sentence planning (see below for a more detailed analysis). A group of trained coders (2 senior and 2 junior coders) marked these temporal boundaries. The senior coders had demonstrated inter-rater agreement rates of 96% and 97% for the N1 and N2 onset times, respectively, on the data from 3 PWA (r's > .96, p < .0001). A disagreement was defined by a difference greater than 50 milliseconds between the two coder's measures. The coders worked on each participant's data in pairs (1 junior coder, 1 senior coder) with disagreements resolved by consensus.

Eye movement data. Each participant's eye fixations were tallied into fixations to the Agent and Theme characters of the target picture. These areas of interests (AOI) were pre-defined during experimental set-up using free-shaped line drawings surrounding each character with approximately 2 visual degrees of margin. Fixations that fell within the AOI before the participant's eye moved out of the AOI were summed to compute the total fixation duration to Agent or Theme. For visualization, the fixation data were aggregated into 16 millisecond bins time-locked to the onset of the picture (Figure 2).

The temporal boundaries obtained from the speech onset data analysis above were aligned with the fixation data to create 5 different sentence regions following previous eyetracking sentence production studies (Griffin & Bock, 2000; Mack et al., 2017; van de Velde, 2014). They included: (1) from the picture onset to 400ms region or apprehension phase, (2) 400-800ms from picture onset, (3) from 800ms to N1 onset, (4) after N1 onset until N2 onset (N1-N2), and (5) after N2 onset until the end of trial (N2-end). Within each region of the trial, proportions of fixation time to the Theme or Agent (out of total fixation durations to both Theme and Agent) were computed. Given that there were only two AOIs, an increase in the proportion of fixation time to one AOI (e.g., Theme) necessarily indicates a proportional decrease in the fixation time to the other AOI (e.g., Agent) within the speech region. Therefore, using fixations to an arbitrarily selected AOI (Theme, in this case) as a reference level, we binarized the proportion data for each trial: proportion fixation times to Theme that were greater than .50 were coded as Theme advantage, whereas proportions less than .50 were coded as Agent advantage. These binarized data were entered into statistical analyses. A significant priming effect on eye fixation data was defined by an increased number of trials with Theme advantage in the Theme vs. Agent prime conditions.

Statistical analysis. All data were modeled using mixed-effects logistic regression in SAS (SAS Institute Inc., 2013). All mixed-effects models initially included maximal random structure. In some cases, random structures were reduced in order to achieve model convergence or due to near-zero variance estimation. Specific random structures are detailed below for each model. When an interaction was significant ($p < .05$) in a model, Tukey-Kramer tests were used as follow-up tests.

In order to compare overall proportions of correct responses between HOA and PWA, a mixed-effects model was run, including group (HOA vs. PWA) and prime type (Agent vs. Theme primes) and their interaction as fixed factors. The random structure included by-participant and by-item intercepts and by-participant and by-item slopes on the main effects. To analyze the effects of lexical priming on *off-line syntactic production*, prime type, group, and their interaction were included as fixed factors. The random structure included by-participant and by-item intercepts and by-participant and by-item slopes on main effects. For *eye fixation data*, a three-way model was first run to compare group differences in priming effects by entering group, prime type, and sentence region as fixed factors and by-participant and by-item intercepts as random factors. To test if and at what sentence region each group of participants showed priming-induced preferences in their fixations, a separate set of within-group models were run by entering prime type, sentence region, and their interaction as fixed factors and including the maximal random structure.

Lastly, for the *analysis of individual differences on syntactic processing*, an additional set of mixed-effects models were conducted by entering individuals' syntax processing scores as a predictor for the priming effects in the off-line sentence production and early eye fixation data. The scores obtained from participants with aphasia on the non-canonical sentences of the SPPT and SPC sections of the NAVS were binarized as 'high' and 'low' scores based on a median split and then entered into the model as a fixed factor. It was examined if the syntax score interacts with the prime effect within each model. This analysis was repeated for each test (namely, SPPT and SCT of the NAVS) for both off-line production and eye fixation data. The random structures for these models included by-participant and by-item intercepts.

RESULTS

Production accuracy: One trial was removed from analysis for each group due to experimental errors. This resulted in a total of 719 analyzable trials for HOA (359 for Agent and 360 for Theme prime conditions) and 395 analyzable trials for PWA (197 for Agent and 198 for Theme prime conditions). Table 2 summarizes off-line production accuracy data for both groups and Table 3 summarizes error types produced by PWA. No statistical analysis was conducted for error responses, given that relatively few errors were produced across different error types.

PWA produced fewer correct responses overall than HOA, as indicated by a significant main effect of group, $F(1, 18) = 5.39, p = .032$. There was a significant main effect of prime type, $F(1, 22) = 9.56, p = .005$, indicating that both groups produced more correct target responses in the Agent compared to the Theme prime condition (HOA: 91% vs. 77%; PWA: 79% vs. 65%). The fewer 'correct' responses in the Theme prime condition are due to various non-target structures produced by both groups (e.g., 'the horse is not wanting to move' for 'the horse is being pulled by the woman'; 'the mailman is running away from the dog' for 'the mailman is being chased by the dog'). In addition, PWA produced ill-formed passive attempts (e.g., 'the car is towing by the truck'). However, the interaction between prime type and group was not reliable, $F(1, 1048) = 1.16, p = .282$.

Table 2. Off-line sentence production data. Production accuracy data show proportions of correct (active and passive) responses out of all analyzable responses. Priming effects show proportions of passive or active responses out of all correct responses as an effect of different lexical prime conditions. The numbers in parentheses are raw numbers.

		Prime condition	
Group	Responses	Agent Prime	Theme Prime
Production accuracy			
HOA	% correct (active + passive) responses	91% (328/359)	77% (277/360)
	SE	2.8%	2.5%
PWA	% correct (active + passive) responses	79% (155/197)	65% (129/198)
	SE	5.1%	6.9%
Priming effects			
HOA	% active responses	98% (320/328)	12 % (32/277)
	% passive responses	2% (8/328)	88% (235/277)
	SE	0.7%	4.7%
PWA	% active responses	91% (141/155)	36% (47/129)
	% passive responses	9% (14/155)	64% (82/129)
	SE	3.2%	7.7%

Note: *SE* = Standard Errors; HOA = Healthy older adults, PWA = Persons with aphasia

Table 3. Percent of errors produced (with the number of errors) by PWA following Agent vs. Theme primes.

Error types	Definition	Examples (Target: *A car is being towed by a truck.*)	Agent Prime	Theme Prime
Non-target structure	A legitimate and grammatically correct sentence response that is neither an active nor a passive structure	*Truck and car are on the road.*	38% (16/42)	46% (32/69)
Non-sentence	String of words without a lexical verb	*Truck is… car*	5% (2/42)	9% (6/69)
Role reversal	Thematic roles are reversed in the correct structure	*Truck is being towed by the car*	14% (6/42)	3% (2/69)
Morphological	Incorrect passive morphology or other morphological errors	*The car is towing by the tow truck*	0 (0/42)	6% (4/69)
Argument structure	Omitted or incorrectly produced obligatory arguments	*Towed by a tow truck*	5% (2/42)	12% (8/69)
Lexical	Noun or verb substitutions, including verbs with incorrect argument structure	*The truck driving the car*	24% (10/42)	3% (2/69)
Other	A response with two or more errors, unintelligible or no response	*I don't know*	14% (6/42)	22% (15/69)
Total			100% (43)	100% (69)

Note: PWA = Persons with aphasia

Priming effects on off-line syntactic production: Table 2 also summarizes off-line production of the alternating syntactic structures under different prime conditions (see Appendix A for individual data). The results revealed a significant main effect of prime type, ***F* (1, 25) =248.17, *p* < .001**, indicating that participants overall produced more passive responses than active responses in the Theme vs. Agent prime condition. The main effect of group was also significant, indicating that PWA in general produced fewer passive responses compared to HOA, ***F* (1, 20) = 5.58, *p* = .028**. Importantly, there was a significant interaction between the prime type and group, ***F* (1, 752) = 15.34, *p* < .001**. Although both HOA and PWA showed a large priming effect, the magnitude of priming was significantly greater for HOA, ***t* = 16.76, *p* < .001, Cohen's *d* = 4.26**, compared to PWA, ***t* = 7.31, *p* < .001, Cohen's *d* = 2.81**.

Priming effects on eye fixations: Table 4 summarizes mean proportions of fixation time to Agent and Theme characters across different speech regions. Figure 3 shows changes in the proportions of fixations to Theme (out of all fixation time to Agent and Theme) over the course of sentence production between the Theme and Agent prime conditions. The results from the overall mixed-effects model indicate significant main effects of group, ***F* (1, 4070) = 4.30, *p* = .038,** and sentence region, ***F* (4, 4070) = 9.15, *p* < .001**. There were significant two-way interactions between group and region, ***F* (4, 4070) = 3.29, *p* = .010**, and between prime and region, ***F* (4, 4070) = 46.60, *p* < .001**. Importantly, there was a significant group x prime type x region interaction, ***F* (4, 4070) = 3.88, *p* = .003**. All the other effects were not significant, ***F*'s < 0.30, *p*'s > .582**.

Separate logistic mixed-effects models conducted within each group revealed that for HOA, the main effects of prime type, ***F* (1, 30) = 0.45, *p* = .509**, and region, ***F* (4, 69) = 0.36, *p* =. 838,** were not significant. However, the interaction between prime and region was significant,

***F* (4, 2679) = 18.88, *p* < .001**. HOA showed more Theme advantage trials in the Theme prime compared to the Agent prime condition in the first 400 ms from picture onset, indicating early divergent fixation patterns from the apprehension stage, ***t* = 2.37, *p* = .017**. The priming effect continued to be significant during the 400-800 ms region, ***t* = 3.61, *p* = .003**. This indicates that HOA continued to linguistically encode the Theme as the subject of the sentence by retrieving the name of the character when producing passives in the Theme vs. Agent prime condition. The priming effect did not reach significance during the 800ms - N1 region, ***t* = 0.30, *p* = .764**. During the N1-N2 region, HOA showed reduced Theme advantage trials in the Theme vs. Agent prime condition, ***t* = -6.51, *p* < .001**. This reversed Theme advantage for the Agent prime condition indicates that HOA were more likely to fixate at the Theme, encoding it as the sentential object, when producing active compared to passive sentences. They showed increased Theme advantage again in the Theme prime condition after N2 onset until the end of the trial (N2-end region), ***t* = 2.07, *p* = .038**.

For PWA, the main effect of region, ***F* (4, 35) = 3.18, *p* = .025**, and the interaction between prime type and region, ***F* (4, 940) = 6.41, *p* < .001**, were significant. The main effect of prime type was not reliable, ***F* (1, 17) = 0.67, *p* = .425**. Different from HOA, PWA did not show increased Theme advantage trials following Theme primes during the apprehension phase (picture onset – 400ms), ***t* = 1.24, *p* = 0.216**. PWA showed equally distributed fixations to the Agent and Theme regardless of prime conditions. However, the main effect of priming was significant for the 400-800ms region, indicating that PWA spent more time encoding the Theme as the grammatical subject of passive responses in the Theme vs. Agent prime conditions at a later sentence region, ***t* = 2.10, *p* = .035**. No reliable difference was found in trials with Theme advantage during the 800ms – N1 onset region, ***t* = 1.41, *p* = .157**. Similar to HOA, after N1

onset and before production of N2 (N1-N2 region), PWA showed significantly more Agent advantage trials following Theme vs. Agent primes, indicating linguistic encoding of the Agent as the grammatical object of the sentence in passive responses, $t = -3.78, p < .001$. There was no effect of prime type in the sentence final, N2-end, region, $t = 1.20, p = .228$.

Figure 2. Eye movement data for healthy older adults (HOA) and persons with aphasia (PWA), correct trials only. The x-axis indicates the time from picture onset in milliseconds. The y-axis indicates the proportion of fixations to the Theme, out of all fixations to the Agent and Theme. Vertical lines indicate different speech regions. The N1 and N2 onset times are averaged across the prime conditions.

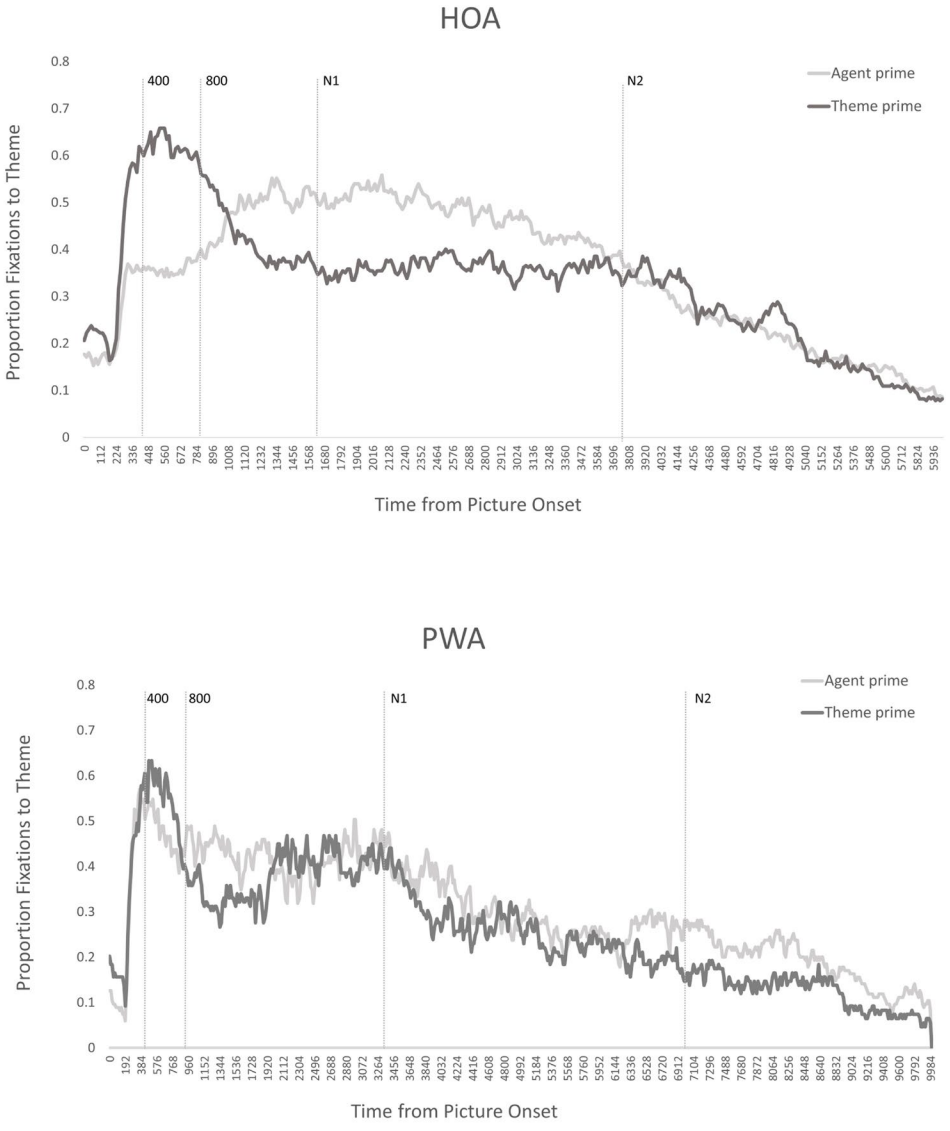


Table 4. Proportions of fixation durations to Agent and Theme characters across different speech regions (with standard errors), correct responses only.

		Sentence Regions				
Prime condition	AOI	400ms	800ms	800ms-N1	N1-N2	N2-end
Healthy Older Adults (HOA)						
Agent prime	Agent	0.53	0.55	0.44	0.22	0.47
	Theme	0.47	0.45	0.56	0.78	0.53
	SE	(0.02)	(0.03)	(0.02)	(0.02)	(0.03)
Theme prime	Agent	0.33	0.28	0.43	0.59	0.34
	Theme	0.67	0.72	0.57	0.41	0.66
	SE	(0.03)	(0.02)	(0.03)	(0.03)	(0.03)
Personss with Aphasia (PWA)						
Agent prime	Agent	0.48	0.47	0.58	0.31	0.44
	Theme	0.52	0.53	0.42	0.69	0.56
	SE	(0.05)	(0.04)	(0.04)	(0.02)	(0.04)
Theme prime	Agent	0.42	0.33	0.53	0.51	0.38
	Theme	0.58	0.67	0.47	0.49	0.62
	SE	(0.03)	(0.04)	(0.04)	(0.04)	(0.05)

Note: AOI = Area of Interest

Analysis of individual differences in syntactic processing: Figure 3 shows priming effects on off-line sentence production (top) and eye fixations occurring in the first 400 milliseconds from picture onset (bottom) as an effect of PWA's median-split based performance on the tests of syntactic processing. For off-line sentence production data, when the SPPT scores were entered as a fixed factor into a mixed-effects model, there was a significant main effect of prime type, $\boldsymbol{F}$ **(1, 264) = 52.24,** $\boldsymbol{p}$ **< .001**, but no effect of SPPT, $\boldsymbol{F}$ **(1, 264) = 0.33,** $\boldsymbol{p}$ **= .567**. Importantly, the SPPT scores interacted with the prime type, $\boldsymbol{F}$ **(1, 264) = 16.16,** $\boldsymbol{p}$ **< .001**, such

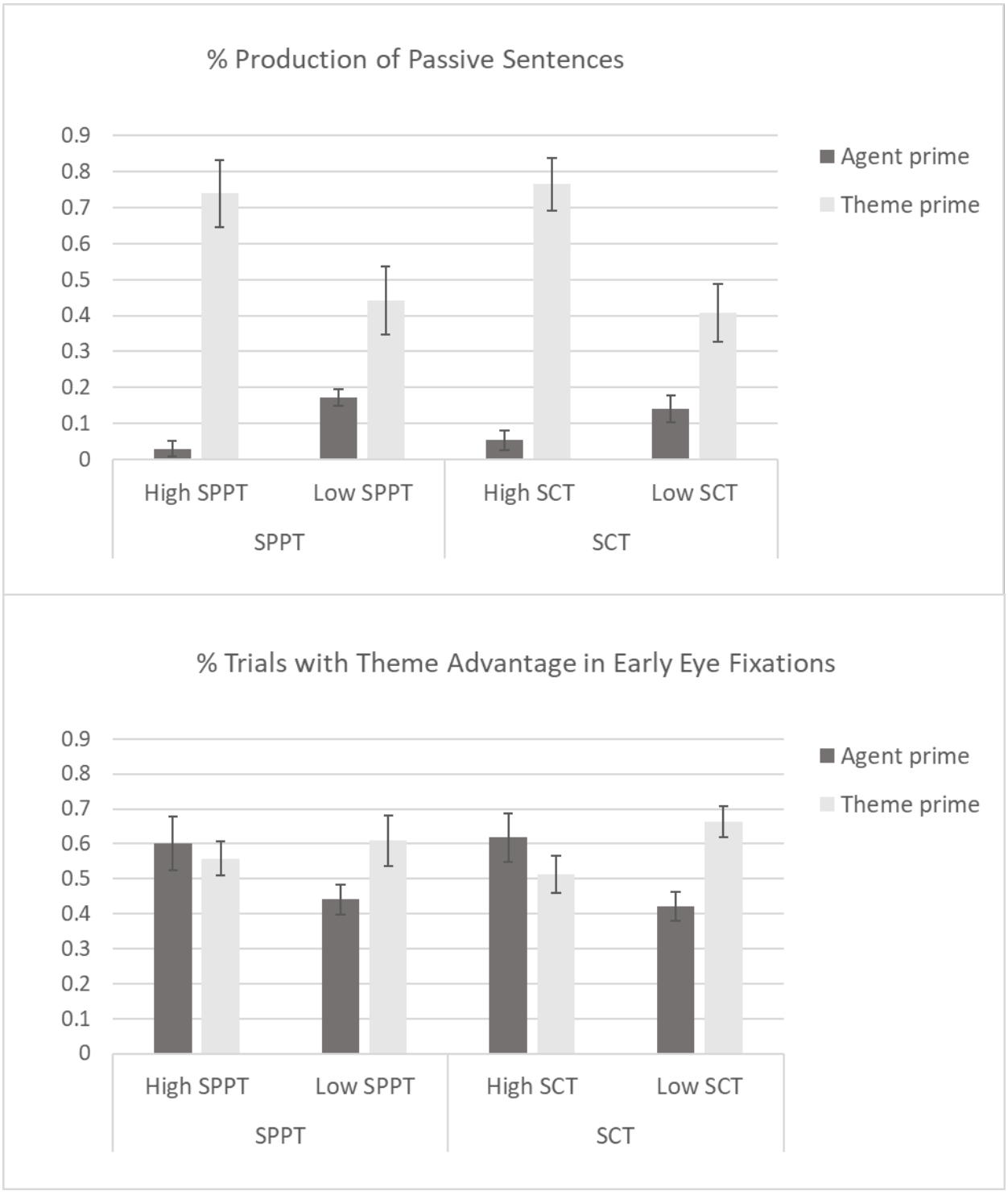
that participants who showed higher scores on the test demonstrated greater ability to produce alternating syntactic structures in response to lexical priming. Parallel results were found in the model including the SCT scores as a fixed factor. The effect of SCT was not reliable, ***F* (1, 255) = 0.56, *p* = .453**. However, the main effect of prime type, ***F* (1, 18) = 42.06, *p* < .001**, and the interaction between the SCT scores and the prime type was significant, ***F* (1, 255) = 9.78, *p* = .002**, indicating that PWA whose syntactic comprehension was better preserved showed greater priming effects.

For the eye fixation data, when the participants' SPPT or SCT scores were entered into the mixed-effects models as a fixed factor, none of the main effects or the 2-way interaction was significant for SPPT scores, ***F*'s < 1.29, *p*'s > .258**, or for SCT scores, ***F*'s < 3.35, *p*'s > .068**. These results indicate that individual participants' scores on the SPPT and SCT did not reliably modulate degrees of lexical priming effects on early fixations to Agent and Theme, different from the results from off-line production.

DISCUSSION

Efficiency in language production is often characterized by speakers' ability to take advantage of both structural and word-level information that becomes accessible in an ever-changing language environment as a way to ease grammatical encoding processes (Ferreira & Bock, 2014 for review). While deficits in sentence production are common in PWA, little systematic research is available on what information effectively guides message-structure encoding in aphasia. A line of previous studies has shown that increased availability of syntactic structures via structural priming effectively facilitates message-structure production in PWA (e.g., Cho-Reyes et al., 2016; Lee et al., 2019; Man et al., in press; Yan et al., 2018). This study

Figure 3. Priming effects on off-line sentence production (top) and early eye fixations (bottom) as an effect of PWA's scores on syntax processing tests (SPPT= Sentence Priming Production Test; SCT = Sentence Comprehension Test; errors bars = standard errors).



examined whether or not word-driven production of syntactic structures is also preserved in persons with mild-to-moderate aphasia by testing how varying lexical accessibility of Agent and Theme characters influences off-line and on-line (eye fixations) production of active/passive alternations.

With regard to off-line production, PWA demonstrated preserved ability to flexibly produce sentence structures that allow earlier production of the primed word. Both HOA and PWA showed a robust tendency to produce passive structures over active structures when the Theme noun was primed compared to when the Agent noun was primed. Although the priming effect was reduced in PWA compared to HOA, as indicated by the significant prime by group interaction in the mixed-effects model, the magnitude of priming for PWA was still large (Cohen's $d = 2.81$). These findings suggest that varying degrees of lexical accessibility 'drive' syntactic choices that speakers with mild-to-moderate aphasia make during language production, similar to what has been shown in unimpaired speakers (Bock et al., 1992; Gleitman et al., 2017; McDonald et al, 1993; Slevc, 2011). Along with the findings from previous structural priming studies with aphasia, the current data suggest that both structural and word-level information modulate message-to-structure encoding processes in speakers with aphasia.

In addition to the group data analysis, an analysis of individual data revealed that lexical priming effects were greater for PWA with relatively preserved syntactic processing ability. PWA who showed higher scores on clinical tests of production and comprehension of non-canonical sentences (NAVS, Thompson, 2011) demonstrated greater ability to produce sentence structures that allow earlier production of the primed word. This finding is in line with the idea that successful use of word-driven production pre-supposes relatively preserved syntactic ability (deSmedt, 1990). Further, the findings suggest that the extent to which either structural or word-

level cues are effective may vary across different individuals with aphasia depending on the nature and severity of individuals' deficits. For example, structural cues may be more effective for individuals with more severe syntactic deficits (Cho-Reyes et al., 2016; Hartsuiker & Kolk, 1998; Lee et al., 2015). For individuals whose syntactic processing is relatively preserved, both structural and word-level cues may effectively guide choices that PWA make in message-to-sentence production, similar to what has been shown in healthy speakers. Clinically, these findings suggest that individuals' syntactic deficits should be considered when using different types of cues to assess or elicit production of target syntactic structures. Future work directly comparing relative effects of word- and structure-level primes in the same group of PWA may inform cuing hierarchy for sentence production treatments. Additionally, given that the current study included a relatively small number of participants with mild-to-moderate aphasia, more research is needed to replicate current findings in a larger sample of individuals with more diverse aphasia profiles and severity levels.

With regard to real-time sentence planning processes, the two groups showed different results. HOA showed eye fixations that are consistent with word-driven incremental planning. They showed priming-induced divergence in fixations from the earliest stage of sentence planning, within 400 milliseconds from picture onset, as indicated by increased fixation time to the Theme over Agent character in the Theme prime compared to the Agent prime condition. Then, they continued to encode the Theme up to approximately 800 milliseconds post picture onset, reflecting linguistic encoding of the Theme as the sentential subject, which is required for correct production of passive structures. These patterns of eye fixations indicate that increased accessibility of the Theme noun via an auditory prime drew their attention to the Theme character immediately after picture onset, precipitating the rest of the sentence formulation

process. Furthermore, these results are consistent with previous eyetracking studies where healthy young adults showed word-driven incremental planning (Gleitman et al., 2007; see also van de Velde et al., 2014).

PWA, on the other hand, showed eye movements that are inconsistent with word-driven incremental planning. They showed priming-induced divergence in fixations more slowly, following non-preferential fixations to Agent and Theme during the apprehension stage. However, PWA showed a significant priming effect in the 400-800 ms region, as seen in HOA, suggesting that they were sensitive to lexical priming and that they were able to encode the grammatical subject of target sentences correctly in response to priming. Even the PWA with relatively preserved syntactic ability showed no differences in early fixations, indicating that they may still have to rely on atypical sentence planning processes in order to produce typical off-line performance. The findings also suggest that the reduced use of word-driven incremental planning in our PWA is more likely to be reflective of cognitive processes underlying their sentence production such as pre-activation of message elements, rather than an artifact of random choices that PWA made during early apprehension of a visual scene.

Overall, the current results revealed that PWA used a qualitatively different sentence planning strategy from HOA in real-time, even when they successfully demonstrated word-driven production in off-line production (Lee & Thompson, 2011a; 2011b; Lee et al., 2015). Specifically, their eye movement patterns are more consistent with the predictions from structure-driven incremental planning, whereby early non-differential fixations to event characters do not predict upcoming sentence form. The advanced planning processes observed in our PWA may reflect a strategy that could ease sentence formulation processes in PWA, as proposed in earlier eyetracking studies with PWA (Lee & Thompson, 2011a, b; Lee et al., 2015;

Mack et al., 2017). Pre-activating lexical concepts of the message elements may ease demands for lexical retrieval for PWA during sentence production. It is also possible that holistic encoding of message elements and their event structure facilitated the process of encoding the 'suitable' subject for PWA, thereby easing both lexicalization and structure building processes during sentence formulation (Lee et al., 2015; Mack et al., 2017). Further research is needed to better identify what specific types of planning happened during the advanced apprehension of the event scene in PWA.

In conclusion, the current study has identified a set of important findings on sentence production in aphasia, by examining whether word-driven production remains preserved in PWA during both off-line and on-line (eyetracking) sentence production. It was demonstrated that varying degrees of lexical accessibility significantly influences choices that PWA make during syntactic (active/passive) production, as shown in healthy speakers. This finding suggests that word-level cues can effectively drive syntactic production in aphasia. At the individual level, the effect of lexical priming on syntactic production was greater for individuals whose syntactic capacity remains relatively preserved. However, PWA did not show word-driven incremental planning in eye fixation data. Their successful word-driven production was associated with advanced processing of both characters during the earliest stage of sentence planning, different from HOA who showed word-driven processes in both off-line and real-time (eye fixations) production.

Appendix A. Off-line priming results for individual participants with aphasia.

	Agent prime		Theme prime	
Participant	% active responses	% passive responses	% active responses	% passive responses
A01	85.7	14.3	44.4	55.6
A02	88.9	11.1	35.3	64.7
A03	93.3	6.7	26.7	73.3
A04	100.0	0.0	18.2	81.8
A05	80.0	20.0	81.8	18.2
A06	100.0	0.0	0.0	100.0
A07	90.0	10.0	75.0	25.0
A08	72.7	27.3	28.6	71.4
A09	100.0	0.0	12.5	87.5
A10	72.7	27.3	37.5	62.5
A11	100.0	0.0	60.0	40.0

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