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Word Learning in Aphasia

Treatment Implications and Structural Connectivity Analyses

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Objective: Of current interest in aphasia research is the relevance of what we can learn from studying word learning ability in aphasia. In a preliminary study, we addressed 2 issues related to the novel word learning ability of individuals with aphasia. First, as word learning engages large-scale cognitive-linguistic systems (language skills, verbal short-term memory [STM], other memory and executive functions), we probed whether novel word learning practice in 3 people with aphasia could stimulate these language-related systems. Second, as lesion correlates affecting word learning in aphasia remain unclear, we examined whether the structural integrity of the left arcuate fasciculus (AF) in the same 3 individuals is related to outcomes of novel word learning practice. **Method:** To stimulate word learning systems, our 3 participants practiced for 4 weeks with an explicit novel word—novel referent word learning task, adopted from the Ancient Farming Equipment learning paradigm (Laine & Salmelin, 2010). The participants' progress on receptive and expressive novel word learning was followed up, and their language and verbal STM abilities as well as single-session novel word learning (Learning to Name Aliens by Gupta, Martin, Abbs, Schwartz, & Lipinski, 2006) were tested before and after the practice period. To address the second question, we analyzed the participants' structural magnetic resonance images with respect to the integrity of the left AF and its overlap with the lesion areas. **Results:** All participants showed some receptive word learning in the trained task, as well as improvements in verbal STM span at posttesting. Two of the 3 participants also showed improved performance on some of the language outcome measures. One participant with a partially spared left AF, especially temporoparietal connections, exhibited better word learning performance than the other 2 who had larger damage and disconnection of the AF. **Conclusions:** Although the present results are preliminary, they open the possibility that novel word learning practice in aphasia may stimulate

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remaining word learning mechanisms in aphasia and thereby influence language and verbal STM abilities. These results also suggest that preservation of novel word learning ability in aphasia in part depends on the integrity of the left arcuate track. **Key words:** *anomia*, *aphasia*, *aphasia treatment*, *arcuate fasciculus*, *short-term memory*, *word learning*

RECENT YEARS have witnessed a growing research interest in word learning ability in aphasia, its neural underpinnings, relationships with other cognitive-linguistic measures, and significance for treatment outcomes (e.g., Breitenstein et al., 2005; Dignam et al., 2016; Grossman & Carey, 1987; Kelly & Armstrong, 2009; Martin, Schmitt, Kamen, Bunta, & Gruberg, 2012; Peñaloza, Rodriguez-Fornells, Rubio, De Miquel, & Juncadella, 2014; Tuomiranta et al., 2013; Tuomiranta, Rautakoski, Rinne, Martin, & Laine, 2012). This interest has been prompted by advancements in neurocognitive research on word learning in individuals without neurological impairments that has highlighted the neural architecture of novel word learning (e.g., Davis & Gaskell, 2009; Laine & Salmelin, 2010; Rodríguez-Fornells, Cunillera, Mestres-Missé, & de Diego-Balaguer, 2009; Tagarelli, Shattuck, Turkeltaub, & Ullman, 2019) and the integral involvement of verbal short-term memory (STM) and other cognitive-linguistic abilities in word learning (e.g., Martin & Saffran, 1999). Moreover, it has been argued that the ability to learn is a key factor in aphasia rehabilitation (Hopper & Holland, 2005) and that our treatment approaches would benefit significantly from a theory of learning to help us understand how a positive treatment change is achieved (Ferguson, 1999).

A COGNITIVE MODEL OF WORD LEARNING AND WORD PROCESSING

How do we learn new words? Receptively, input processes support the establishment of mental representations of the word's phonological composition and lexical form that become linked with a referent and its semantic features. Learning the expressive form of a novel word involves linking the semantic features and lexical form of the word to its output phonological representations. This learning process is supported by verbal STM as well as access to and retrieval of known words in one's vocabulary. Current theories of the nature of aphasia hypothesize that impairment of short-term maintenance of word representations, a form of verbal STM, is an integral component of the word retrieval impairments in aphasia (Martin, Minkina, Kohen, & Kalinyak-Fliszar, 2018; Martin & Saffran, 1997; Martin, Saffran, & Dell, 1996). On this view, understanding the relationships of verbal STM capacity, word processing and word learning should provide insights into our approaches to remediation of lexical impairments in aphasia. To understand how word learning may impact treatment, we must first examine how new word learning and word retrieval interact.

Gupta (2012) proposed that word learning involves a "confluence" of memory systems, including short-term, procedural and declarative memories. In his 2003 computational model, Gupta outlined the relation of verbal STM to word processing and word learning (Figure 1). This model links together serial recall, nonword repetition, and lexical access. It postulates a sequence memory component of STM that acts as a phonological store and ordering device. The sequence memory captures the activation of linguistic representations via connections to both the lexical (word) and sublexical (phonological) levels and supports the sequential recall of information together with other verbal STM processes. The sequence memory component is not in itself a word learning mechanism, but it allows for long-term learning by establishing connections between the lexical and sublexical levels so that novel information will be consolidated in serial order. Assuming that these components are malleable to training, this model opens up some intriguing potential avenues for aphasia treatment. For example, repeated practice with novel word

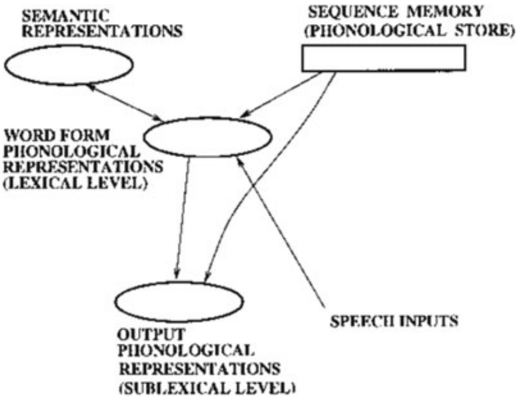

Figure 1. Gupta's (2003) computational model of the relationship between lexical access and verbal short-term memory. From "Examining the Relationship Between Word Learning, Nonword Repetition, and Immediate Serial Recall in Adults," by P. Gupta, 2003, *The Quarterly Journal of Experimental Psychology: Section A, 56*(7), pp. 1213–1236. Copyright 2003 by SAGE Publications Ltd. Reprinted with permission.

learning might stimulate all the components involved, including verbal STM and lexical processing.

Gupta's model provides an account of the influence of verbal STM mechanisms on word and nonword repetition and immediate serial recall (e.g., digit span), which are both essential to learning novel words. There is evidence to support these hypothesized relationships. Through various word learning, nonword repetition, and immediate recall tasks, Gupta found positive correlations between all three measures, supporting his model and the underlying role of verbal STM among the three tasks (Gupta, 2003). Additional research further establishes a connection between measures of verbal STM and word learning. For example, verbal STM has been shown to support both lexical retrieval and learning processes in healthy adults (e.g., López-Barroso et al., 2011) and individuals with aphasia (Martin & Saffran, 1999). Moreover, studies of novel word learning in several populations have provided insight into the cognitive-linguistic and neural systems that support language. In children, it has been found that digit span and nonword repetition performances are related to vocabulary knowledge and faster learning of novel words (Gathercole & Baddeley, 1989). Nonword repetition also predicts successful learning of English as a second language (Service, 1992). Studies of verbal learning abilities in adults after brain damage indicate that phonological STM is associated with learning of unfamiliar words. Verbal STM and lexical-semantic abilities in aphasia have also been implicated in learning novel words (Dignam et al., 2016; Gupta, Martin, Abbs, Schwartz, & Lipinski, 2006; Martin et al., 2012) and word sequences (Dignam et al., 2016; Martin & Saffran, 1999). Finally, there is some evidence that novel word learning ability is predictive of outcomes of anomia treatment in aphasia (Dignam et al., 2016).

NEURAL CORRELATES OF WORD LEARNING ABILITY

Several fiber tracks crossing over the left hemisphere connect frontal regions with parietal and temporal structures. The dorsal pathway projects posteriorly involving parietal regions and projects to temporal structures (indirect pathway), whereas the ventral pathway directly projects through temporal regions (dual-stream model; Hickok & Poeppel, 2007). The ventral pathway is involved in processing semantic information and meaning acquisition during language learning (Hagoort, Hald, Bastiaansen, & Petersson, 2004), including several fiber pathways such as the uncinate fasciculus (UF), inferior longitudinal fasciculus (ILF), and inferior fronto-occipital fasciculus (IFOF), among others. The dorsal stream is served by the arcuate fasciculus (AF) with its three different segments, and its role in speech processing and language production has been clearly established (Rodríguez-Fornells et al., 2009). Here, we focused especially on the AF, as it has been shown to play a role in successful novel word learning (López-Barroso et al., 2013; Rodríguez-Fornells et al., 2009) and foreign language imitation ability (Vaquero, Rodríguez-Fornells, & Reiterer, 2017) in healthy participants, as well as in language acquisition after perinatal stroke (François et al., 2016). The AF is mainly responsible for conveying information through the dorsal language stream, which is known to contribute to sound-to-articulation transformations (Hickok & Poeppel, 2007; Liberman & Mattingly, 1985). Neuroanatomically, the AF has been characterized by a three-branch division: the *long segment*, connecting the superior posterior temporal regions with the inferior frontal gyrus (Broca's region); the *anterior segment*, connecting the inferior parietal lobe with the inferior frontal regions; and the *posterior segment*, connecting the posterior superior temporal regions to the inferior parietal lobe (Catani et al., 2007; Catani, Jones, & Ffytche, 2005; Dick & Tremblay, 2012). Damage to the AF has been associated with impairments of repetition, phonological processing, and fluent speech production (Fridriksson, Guo, Fillmore, Holland, & Rorden, 2013; Geller, Thye, & Mirman, 2019; Geva, Correia, & Warburton, 2015; Griffis, Nenert, Allendorfer, & Szaflarski, 2017; Ivanova et al., 2016; Jang, 2013; Marchina et al., 2011; Tak & Jang, 2014; Torres-Prioris et al., 2019). Moreover, in healthy participants, variability in the integrity of the AF has been associated with audio-motor integration (Assaneo et al., 2019), phonological processing (Saygin et al., 2013; Thiebaut de Schotten, Cohen, Amemiya, Braga, & Dehaene, 2012; Vandermosten, Boets, Wouters, & Ghesquière, 2012; Yeatman, Dougherty, Ben-Shachar, & Wandell, 2012), working memory (Myers et al., 2014), and development of reading skills in children (Myers et al., 2014).

Overall, the integration of new words into the mental lexicon involves an interplay between cortical and hippocampal systems (e.g., Davis & Gaskell, 2009; O'Reilly & Norman, 2002), where the dorsal language stream plays an important role by engaging verbal STM and its phonological storage component for rehearsal and maintenance of to-be-learned words (Baddeley, 1992; Baddeley, Gathercole, & Papagno, 1998; Gupta, 2003; López-Barroso et al., 2015). This same system supports processing of familiar words, and it is through this link that stimulation of word learning mechanisms in novel word learning tasks might lead to greater verbal STM capacity and improved access to and retrieval of known words.

NEW WORD LEARNING IN APHASIA

Previous research on new word learning in aphasia has examined implicit versus explicit as well as expressive versus receptive word learning. Findings indicated that word learning varies significantly in people with aphasia (PWA), with some learning only receptively and others showing greater expressive word learning as well (e.g., Gupta et al., 2006; Tuomiranta et al., 2013; Tuomiranta, Grönholm-Nyman, et al., 2011). The modality of learning (e.g., via auditory-phonological vs. visual-orthographic input) also can impact learning, contributing further to individual variability (Tuomiranta et al., 2013). Word learning in aphasia has also been observed in more natural and ambiguous contexts (Peñaloza et al., 2016, 2017). Some studies have shown maintenance of the novel words up to 6 months (Tuomiranta et al., 2013; Tuomiranta, Grönholm-Nyman, et al., 2011), suggesting that the learned words were successfully integrated into the mental lexicon.

Studies of word learning in aphasia have also provided some insight into the lesion correlates of word learning ability. Based on gross lesion localization of a group of individuals with aphasia, Peñaloza et al. (2014) found that the integrity of the left frontal lobe was an important structural correlate of word learning. Word learning also has been linked to areas of the neocortex that are part of the dorsal and ventral networks, such as the left temporal lobe and left inferior parietal lobe (Breitenstein et al., 2005; Davis & Gaskell 2009; Raboyeau et al., 2004). Laine and Salmelin (2010) provide a review of studies that use new word learning to identify the neural underpinnings of the word learning system. Using mgnetoencephalography (MEG), Cornelissen et al. (2004) found increased activation in the left inferior parietal lobe when neurologically intact adults named novel items they had learned with the so-called Ancient Farming Equipment paradigm (Laine & Salmelin, 2010). Similarly, Cornelissen et al. (2003) found anomia treatment-related activation change in the left inferior parietal lobe in participants with aphasia. The authors attributed this to more effective phonological encoding and retrieval of the trained items, that is, the phonological storage component of the verbal STM. Tasks involving verbal STM have been found to activate frontoparietal systems where the phonological store (sequence memory according to Gupta, 2003) is thought to be related to activity in the left parietal lobe. Although various neuroimaging studies have found some differences in activation during retrieval of newly learned words, these differences may be due to the specific task used in each study. Despite these differences, there appears to be a clear connection of word learning to areas of the cortex responsible for semantic and phonological processing, as well as hippocampal activation for episodic memory.

THE CURRENT STUDY

The studies mentioned earlier indicate variability in the preservation of new word learning abilities in aphasia and suggest roles for cognitive-linguistic abilities (verbal STM, lexical-semantic processing) and the integrity of specific neural regions, such as the left frontal region and the left AF. However, this evidence is limited, and additional studies are needed to further our understanding of the cognitive-linguistic and neural underpinnings of word learning in PWA. In this study, we focused on two preliminary objectives. First, we aimed to stimulate the word learning system in PWA through intensive new word learning practice. This attempt was intended to determine whether the processes engaged in word learning would affect verbal STM and linguistic performances, as Gupta's (2003) model would suggest. We assessed and stimulated novel word learning mechanisms with an explicit novel word—novel picture association task, which has been proposed to provide a relatively "pure" measure of the functionality of the word learning system (Tuomiranta, Grönroos, Martin, & Laine, 2014).

Second, on the basis of studies that highlight the crucial role of the dorsal language pathway (AF) in novel word learning, we aimed to explore how the structural integrity of this dorsal pathway was related to receptive versus expressive new word learning success in our three PWA.

Thus, the specific objectives for this study were as follows:

1. To determine whether repeated practice in learning novel words and their referents would be associated with improvements in verbal STM, input and output language processing (word production, word comprehension, and repetition), or in novel word learning as measured by a different single-session learning task.
2. To explore whether the structural integrity of important left hemispheric language pathways, the left AF as well as ventral pathways, is related to novel word learning outcomes. We assumed that individuals with more severe damage to these pathways would have more difficulties on word production, repetition, and language learning.

METHODS

Participants

We enrolled three monolingual English-speaking males with chronic aphasia (K.T., U.P., and C.N.) in this study. They presented with aphasia following an ischemic or hemorrhagic cerebrovascular accident involving the left middle cerebral artery (MCA) and leading to a single left hemisphere cortical lesion. They were at least 6 months poststroke and had no history of mental illness and/or alcohol or substance abuse. All participants passed a pure tone audiometry hearing screening at 25 dB hearing loss (HL) at 1K, 2K, and 4K Hz for at least one ear and were not observed to have evident hearing difficulty. All three participants met our criteria for visual acuity with at least 20/40 vision (corrected or uncorrected) as measured by the "TumblingE" chart. None of the participants exhibited neglect, but K.T. did wear a magnification device over his right eye to assist with a visual field cut. English was the first language of all participants. We obtained information about the presence of dysarthria or apraxia of speech from medical reports. When this information was not available from the medical reports, and if we suspected the presence of motor speech disturbances, we administered the Apraxia of Speech Rating Scale (Strand, Duffy, Clark, & Josephs, 2014) and the Assessment of Intelligibility of Dysarthric Speech (Yorkston & Beukelman, 1981).

Only one of the participants (C.N.) was reported to have apraxia of speech and this was considered to be mild (see the section on participants). None of the participants reported a history of learning disabilities. The participants were not involved in any additional treatment for the duration of the study.

Participant K.T.

K.T. was a 67-year-old right-handed man with 12 years of formal education. He presented with a left hemisphere MCA infarction, which affected most of the inferior parietal lobule and extended into the superior parietal lobule with white matter tract involvement, as well as the posterior, superior occipital lobe. The posterior portion of the superior temporal gyrus was involved, but the temporal lobe was otherwise intact (see Figure 2). In addition, there was some ischemic damage to the pre-central gyrus without complete infarction of the region (Figure 2). K.T. was 2 years postonset at the time of testing. He presented with a severity rating of 1 out of 5 (1 being the most severe) on the Boston Diagnostic Aphasia Examination (BDAE; Table 1) (Goodglass, Kaplan, & Barresi, 2001) with a language profile consistent with Wernicke's aphasia. His speech was fluent with paragrammatic errors, neologisms, and empty utterances. Auditory comprehension and repetition were reduced throughout testing and in conversation.

Participant U.P.

U.P. was a 53-year-old right-handed man with 14 years of formal education. He

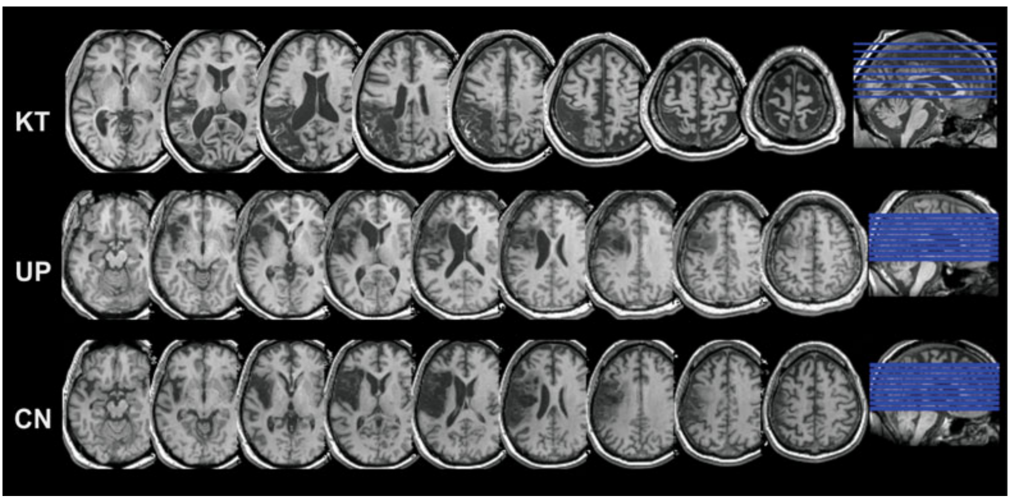

Figure 2. Anatomical depiction of the lesions of the three patients (T1-weighted normalized magnetic resonance axial images, neurological convention used). Corresponding slices chosen are depicted at the right column sagittal view.

Table 1. Boston Diagnostic Aphasia Examination results

Subtest	K.T.	U.P.	C.N.
Severity rating	**1**	4	2
Fluency			
Phrase length	7/7	7/7	**3/7**
Melodic line	7/7	7/7	6/7
Grammatical form	**4/7**	6/7	**4/7**
Conversation/expository speech			
Simple social responses	6/7	6/7	7/7
Complexity index	0.67	0.69	**0.43**
Auditory comprehension			
Basic word discrimination	**22/37**	34/37	36/37
Commands	**5/15**	14/15	15/15
Complex ideational material	**2/12**	10/12	9/12
Repetition			
Words	**5/10**	9/10	10/10
Sentences	**0/10**	5/10	**3/10**

Note. Numbers in bold represent a score falling below the 50th percentile.

presented with a left hemisphere MCA infarction. His extensive left frontal lesion involved the cortex of the posterior two third of the inferior frontal gyrus and subcortical white matter underlying the middle and superior frontal gyri. The anterior superior insular cortex was also infarcted. The temporal lobe was quite well preserved (Figure 2). U.P. was 8 years postonset at the time of testing. His severity rating on the BDAE was 4 out of 5 (mild; Table 1) and his language profile was consistent with anomic aphasia. He performed well on auditory comprehension measures in the BDAE, except for some difficulty with the complex ideational material. Single-word repetition was intact, but sentence repetition was impaired. His speech was fluent with some phonological paraphasias (about one to two per minute).

Participant C.N.

C.N., a 53-year-old right-handed man with 10 years of formal education, presented with a left hemisphere MCA infarction affecting the posterior two third of the inferior frontal gyrus and inferior portions of the middle frontal gyrus. The lesion extended posteriorly to the anterior margin of the angular gyrus. The inferior insula was infarcted, but the temporal lobe was quite preserved (Figure 2). He was 4 years postonset at the time of testing. C.N.'s BDAE severity rating was 2 out of 5 (Table 1), and his language profile was consistent with Broca's aphasia. Medical records reported the presence of mild apraxia of speech. We administered the Apraxia of Speech Rating Scale (Strand et al., 2014), which confirmed this diagnosis. C.N.'s single-word repetition was good but included articulatory errors and phonological paraphasias. Sentence repetition was difficult and conversational speech was agrammatic with some phonological paraphasias and articulatory errors.

Neuroimaging protocol

High spatial anatomical resolution recordings were acquired using a 3T magnetic resonance imaging (MRI) scanner. Whole-brain high-resolution T1-weighted images (166 slice sagittal, repetition time [TR] = 11,668 ms, echo time [TE] = 4.796 ms, inversion time [IT] = 450 ms, flip angle = 12°, FOV = 25.6 cm, 1-mm isotropic voxels) were captured. T2 and FLAIR sequences were also obtained for hemorrhage lesion definition.

For the track-wise lesion analyses explained later, we manually drew the lesion outline on the T1-weighted images in the native space using MRIcron software package (Rorden & Brett, 2000). All lesion outlines were delineated by the same researcher (N.R.) in the axial plane and further smoothed for sharp edges (see Figure 2 for the visualization of lesions). Furthermore, the unified segmentation (Ashburner & Friston, 2005) with medium regularization and cost function masking was applied to the T1-weighted image using the resliced lesion mask in order to obtain the normalization parameters (Andersen, Rapcsak, & Beeson, 2010; Brett, Leff, Rorden, & Ashburner, 2001; Ripollés et al., 2012). Then, using these parameters, both the T1-weighted image and the resliced lesion mask were normalized to MNI152 standard space using Statistical Parametric Mapping (software SPM12) (Welcome Department of Imaging Neuroscience, University College, London, United Kingdom; www.fil.ion.ucl.ac.uk/spm). After the normalization, one of the authors (N.R.) reviewed the individual masks and T1 images, confirming that no distortions occurred. Lesion masks were introduced to BCBtoolkit to obtain probability and proportion of disconnection percentages and the Disconnectome maps for each participant.

For the structural MRI analysis, we followed a procedure used by François et al. (2016) to determine whether the lesion involved classical cortical language areas. Using the NeuroSynth meta-analysis platform (Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011) to search language-related cortical areas, we generated reverse inference map (in MNI space) and then registered it with the T1-weighted images (in native space) of each participant. Finally, the functional MRI (fMRI) meta-analysis was overlapped with the participants' lesions.

Second, a track-wise lesion analysis (Tractotron; Thiebaut de Schotten et al., 2011) was used to accurately delineate the relationships between the precise lesion location and the integrity of the AF. Tractotron toolbox provides a percentage of likelihood for a specific tract to be affected, thus offering relevant information to describe the pattern of damage induced by the lesion as well as the proportion of damage of each track. This calculation was based on the comparison between the voxels depicting lesion distribution and a white matter atlas from a group of healthy volunteers (Rojkova et al., 2016) both within the MNI coordinates (Thiebaut de Schotten et al., 2014). We expressed only the proportion of tract disconnection by the lesion over the dorsal pathway (AF track), including the three segments (anterior or frontoparietal, posterior or temporoparietal, and long or frontotemporal) and the ventral pathway (including IFOF, ILF, and UF; Sierpowska et al., 2019; Torres-Prioris et al., 2019). The proportion of disconnection refers to the percentage of the tract affected by the lesion (computed by the number of overlapping voxels between the probabilistic map of the tract and the lesion map).

It is important to acknowledge the limitations of the track-wise lesion analysis (Thiebaut de Schotten et al., 2011) we used to infer the status of language-related white matter pathways. The imaging protocol for our participants did not include diffusion weighted imaging (DWI) that might have allowed for a fine-grained analysis of white matter pathways using tractography. Nonetheless, we believe the present method provides a reasonable proxy to explore the integrity of critical language pathways. Indeed, different approaches have recently been used to combine lesion delineation in patients with stroke or surgical resection (using structural MRI) with existing white matter atlases derived from diffusion imaging (Forkel & Catani, 2018; Foulon et al., 2018; François et al., 2016; Rojkova et al., 2016, Thiebaut de Schotten et al., 2014; Sierpowska et al., 2019). The reference white matter atlas in the present case (Rojkova et al., 2016) included a sample of 47 healthy volunteers (age range, 22–71 years, mean = 45 years; 24 males; mean years of education, 15). Because of the composition of this white matter atlas, it is important to acknowledge the possible limitations of the comparisons made, especially considering that age, gender, and years of education are important predictors of white matter changes.

We also computed Disconnectome maps using BCBtoolkit (Foulon et al., 2018) to evaluate a given voxel's probability of disconnection (from 0% to 100%) for a given lesion (registered into an MNI space) and considering the interindividual variability of tract reconstructions in a normative DWI tractography data set (as indicated in Thiebaut de Schotten et al., 2015). For each participant, a probability map of disconnection is obtained for a particular lesion, which reflects possible remote effects caused by the focal brain lesion (including regions not directly affected by the lesion).

Study design

The task of new word learning can be very challenging for individuals with aphasia, especially learning their expressive forms. We aimed to minimize any potential frustration of participants as they proceeded through the protocol. For this reason and because this was a proof-of-concept study to determine the feasibility of using novel word learning as a means to improve language abilities in aphasia, we used a single baseline design with various pre- and posttraining measures and probes albeit a multiple baseline design would have been methodologically superior (e.g., Gupta et al., 2006; Martin et al., 2012; Tuomiranta et al., 2014; Tuomiranta, Grönholm-Nyman, et al., 2011). The baseline assessment was conducted expressively and receptively with all items to ensure that all participants were unfamiliar with the training materials. In each session, we trained one module and then probed that module in the following session in an ABA pattern across sessions. Items from Module 1 were trained on Day 1 and probed on Day 2. Items from Module 2 were trained on Day 2 and probed on Day 3. This alternating sequence continued until Session 9. There was a 5-min break between receptive and expressive training. A final test including both Modules 1 and 2 was administered during the last session.

Training stimuli

Twenty novel items for training were chosen from the names developed by Gupta (2003). These were phonotactically balanced for English and one to three syllables in length. The 20 items were grouped into two modules with 10 items each and further subdivided into two five-item training sets: Module 1 = Set 1 and Set 2, and Module 2 = Set 3 and Set 4. Items within a training set did not share initial phonemes, although items within a module did share an initial phoneme. Pictures came from the Ancient Farming Equipment paradigm (Laine & Salmelin, 2010). A list of all training stimuli is provided in Supplemental Digital Content Appendix B (available at: http://links.lww.com/TLD/A62). The stimuli were presented via E-Prime 2.0 computer program. A digitally recorded live female voice presented each item.

Training probes

Before training on Module 2 (second day of training), Module 1 was probed. Each target was presented once with a receptive probe and an expressive probe in the same format as the exposure and practice phases, and with the target appearing with another trained item and two foils.

Training schedule

The training protocol was delivered for 1 hr a day, 2 days a week, for 4 weeks. There were nine training sessions and eight training probes. The first training probe occurred 24 hrs after the beginning of Session 2.

Training procedure

Training targeted receptive and expressive learning and included two phases, exposure and practice. Receptive training was always completed first.

Exposure

The exposure phase was the same for receptive and expressive training: The target was presented four times randomly, among three distractors. The target word was presented auditorily, and the associated image was highlighted by a red box. Of the three distractors, two were foils and were not taught during training whereas one was another learned item. The target appeared on the screen in a randomized position (see Figures 3A [aliens] and 3B [tools]). The participant was asked to repeat the name of the target as it was presented.

Practice

After receptive (or expressive) exposure, a practice test was completed. Participants had four opportunities to identify or name target items per session. For receptive practice, the participant's task was to point to the stated item among four alternatives, without a visual highlighting cue. For expressive practice, the task was to name one of four pictures, which was highlighted on the screen. Examples of these practice tests are shown in Figures 3A and 3B.

Feedback

During the practice phase, the correct response was provided regardless of the participant's response. No feedback was provided during the probes or the 48-hr final posttest. For correct responses, the correct item was highlighted and the item name was confirmed ("Yes, it's . . . "). For incorrect responses, the correct response was given ("It's . . .). This feedback was given once per stimulus item.

Data analysis

Pre- and posttraining tests of language abilities

Outcome measures

We administered the following tests to all participants before and after training to assess any effects of the new word learning training on language and verbal STM abilities:

1. Nonword repetition from the Temple Assessment of Language and Short-Term Memory in Aphasia (TALSA; Martin, Minkina, Kalinyak-Fliszar, & Kohen, 2018);
2. Digit/word spans (repetition and pointing response; measures of verbal STM) from the TALSA;
3. Confrontation picture naming: the Philadelphia Naming Test (PNT; Roach, Schwartz, Martin, Grewal, & Brecher, 1996);
4. Spoken word-to-picture matching: the Peabody Picture Vocabulary Test (PPVT; Dunn & Dunn, 1981) for receptive language and lexical-semantic processing (Tuomiranta, Grönholm-Nyman, et al., 2011);
5. Nicholas and Brookshire's (1993) narratives for discourse analysis.
6. Linguistic and nonlinguistic control tasks included the following:

   a. Oral Reading of Regular and Exceptional Words (Psycholinguistic Assessments of Language Processing in Aphasia, PALPA; Kay, Lesser, & Coltheart, 2009) and
   b. Five-Point Test (Fernandez, Moroni, Carranza, Fabbro, & Lebowitz, 2009), which measures visuospatial learning and is not expected to improve following this training to learn novel words.

7. Finally, we assessed participants' *new word learning ability* pre- and posttraining with a different single-session task based on the "aliens from other planets" novel word learning paradigm outlined by Gupta (2003). This computerized task (Gupta et al., 2006) includes two sets of five aliens whose names were trained receptively and then expressively, each followed by a practice test period (see Supplemental Digital Content Appendix A, available at: http://links.lww.com/TLD/A61).

Corrections for multiple comparisons

While a number of methods are available for correcting for multiple comparisons, some statisticians have argued that these should not be used as they run the risk of Type II errors (e.g., O'Keefe, 2003; Rothman,

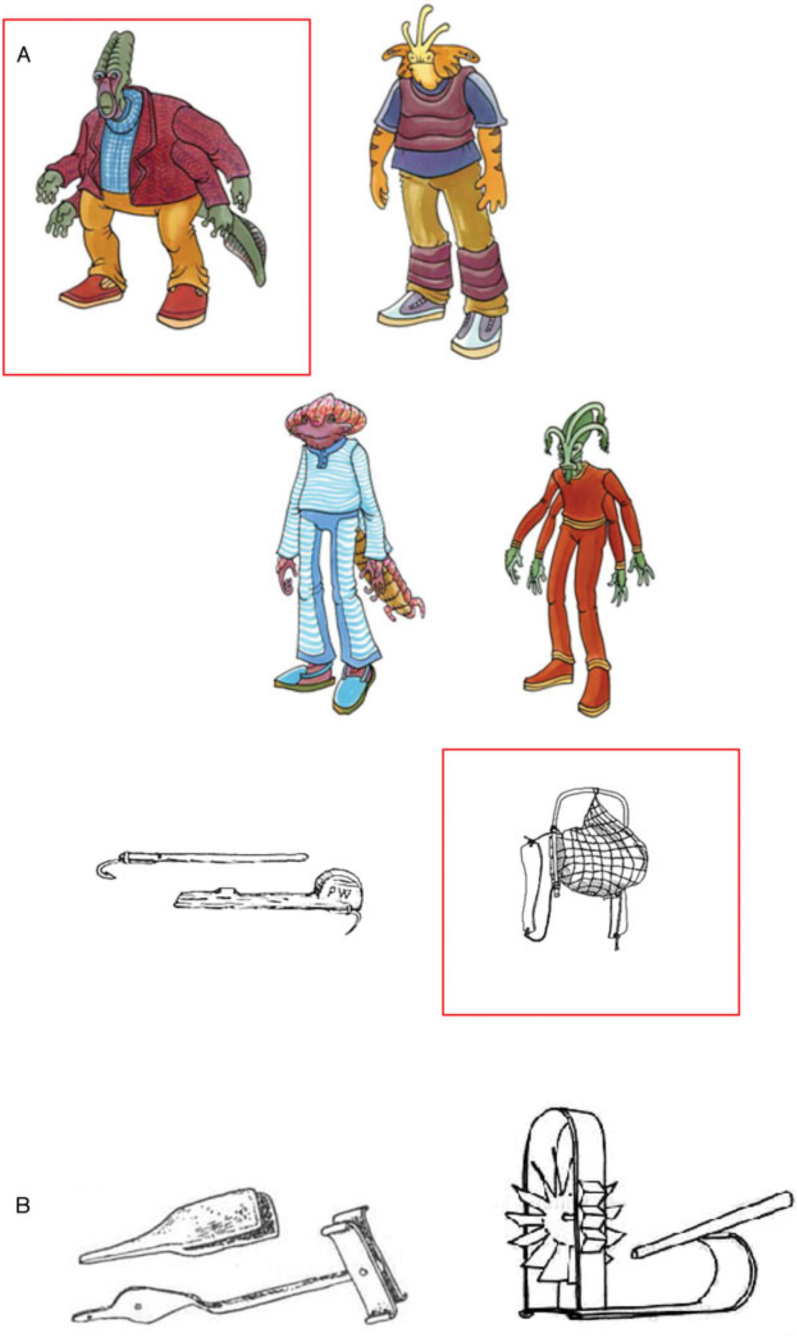

Figure 3. Example screen with presented stimuli. Auditory stimulus was provided along with image. (A) Alien training period from pre/posttest novel word learning task. The target highlighted is “Dunune.” (B) Tool stimuli presented as part of treatment. The target highlighted is “bahv.”

1990). We concur with this viewpoint and would emphasize the need to look at the pattern of results. In other words, the key issue is to decide whether the pattern of results makes sense either theoretically or based on previous research or whether it looks haphazard. Accordingly, the statistical tests reported on the behavioral data later were not corrected for multiple comparisons.

Before training began, all items were presented receptively and expressively to obtain a baseline record of knowledge of the items or any posttraining proportions of change. Two versions of the single-session learning test were created to control for possible effects of item exposure with the items assessed in pretraining that might affect posttraining performance and produce a test–retest confound posttraining. One version was administered before training, and both versions were administered posttraining (U.P. and C.N. received both Version 1 and Version 2, but K.T. received only the first version, as the second version was not part of the protocol when K.T. began training). A list of all trained aliens in this outcome measure is provided in Supplemental Digital Content Appendix A (available at: http://links.lww.com/TLD/A61).

Phonological analysis

Spoken responses were recorded and transcribed for accuracy. The last and best responses were scored for phonological analysis (Martin et al., 2012). Rules for phonological analysis are presented in Supplemental Digital Content Appendix C (available at: http://links.lww.com/TLD/A63). Previous research has shown that participants with aphasia frequently do not demonstrate complete accuracy in their expressive learning of novel words (Martin et al., 2012) but do show improvement in the proportion of phonemes correct, forming responses that increasingly approximate the target word's phonology. Thus, we used the proportion of phonemes correct in serial order and the proportion of names produced correctly as the dependent measures.

Analysis of learning outcomes

Receptive and expressive learning on the training task was evaluated by comparing the proportion of correct items, along with the proportion of correct phonemes for expressive responses from baseline and 48-hr posttraining. We used Fisher's exact test to analyze learning outcomes before and after training and determine significant changes between the pre- and posttraining measures. It should be noted that responses on the PNT were scored and analyzed with both strict and lenient scoring to assess first response and speed of word retrieval. This was done to better evaluate the lexical retrieval process across time when engaged in a naming task and better apply picture naming to functional word finding tasks.

To determine whether there were improvements in discourse abilities after training, we examined changes in the mean proportion of correct information units (CIUs) produced by each client before and after training. We used Nicholas and Brookshire's (1993) discourse tasks (e.g., picture description, story retell) for assessing discourse. On the basis of the performance of the 20 PWA who were reported in Nicholas and Brookshire (1993), Brookshire and Nicholas (1994) proposed that a change of greater than twice the standard error of measurement (SEM) could be considered as a meaningful change. The SEM for proportion of CIUs was 4.2%. This benchmark has been used in treatment studies (e.g., Edmonds, Mammino, & Ojeda, 2014; Wambaugh & Ferguson, 2007) as an indication of improvement in this discourse measure that could be attributed to effects of treatment. Table 2 shows changes in rates of CIUs before and after training for each of the 10 narratives that were administered in this discourse stimulus set. Performance on these narratives was variable, and so for this analysis, we used the average rates of CIUs in the narratives produced by U.P. and C.N. To be considered meaningful, the difference between proportions of CIUs after training had to be 8.4%, that is, twice the SEM of 4.2%.

Table 2. Language tests administered pre- and post-treatment

	K.T.		U.P.		C.N.	
Test	**Pre-Tx**	**Post-Tx**	**Pre-Tx**	**Post-Tx**	**Pre-Tx**	**Post-Tx**
Peabody Picture Vocabulary Test (Dunn & Dunn, 1981)						
Raw score	124	168	157	160	196	200
Standard score	68	79	74	75	89	91
TALSA subtests (Martin, Kohen, & Kalinyak-Fliszar, 2010)						
Nonword repetition ($n = 10$)	0	0	1.8	2	1.8	2.2[a]
Word repetition span (ISO)	0.4	1.2[a]	3.8	3.8	4	4.2
In any order (IAO)	0.4	1.2[a]	3.8	3.8	4	4.2[a]
Digit repetition span (ISO)	1.6	1.4	3.8	4.2[a]	4.6	5
(IAO)	1.6	1.6	4	4.8[a]	4.8	5
Word pointing span (ISO)	1	1.2	3.6	3.4	4.2	4
(IAO)	1.2	1.4	3.6	4	4.2	4.2
Digit pointing span (ISO)	0.8	1.2	3.8	4.2[a]	4.6	4.4
(IAO)	1.0	1.0	3.8	4.8	4.6	4.4
Philadelphia Naming Test (Roach et al., 1996)						
Strict scoring ($n = 175$)	72	72	169	169	166	168
Lenient scoring ($n = 175$)	88	99	172	173	171	173
Discourse (Nicholas & Brookshire, 1993) (proportion CIUs)	0.21	0.18	0.58	0.69[a]	0.70	0.57
New Word Learning Version 1 (Coran, Rosenberg, & Martin, 2016)						
Receptive ($n = 10$)	2	6	10	10	8	10
Expressive ($n = 10$)	0	0	1	1	0	0
New Word Learning Version 2 (Coran et al., 2016)						
Receptive ($n = 10$)	N/A	N/A	N/A	10	N/A	6
Expressive ($n = 10$)	N/A	N/A	N/A	1	N/A	0
PALPA (Kay et al., 2009) Reading						
Regular ($n = 30$)	17	11	20	12	25	28
Exception ($n = 30$)	18	14	25	16[a]	25	26
Five-Point Test (Fernandez et al., 2009) (proportion correct)	0.40	0.33	0.60	0.10	0.54	0.44

Note. IAO = in any order; ISO = in serial order; N/A = not applicable; PALPA = Psycholinguistic Assessments of Language Processing in Aphasia; TALSA = Temple Assessment of Language and Short-Term Memory in Aphasia; Tx = treatment.
[a]Fisher's exact test (two-tailed) was used to calculate significant changes, $p < .05$.

Narratives were analyzed for their inclusion of proportions of closed class words, verbs, and sentences. Word and content repetitions as well as incorrect information were excluded from the overall word count.

RESULTS

Reliability

Interrater reliability for C.N.'s and U.P.'s phonological analysis was assessed using intraclass correlation coefficients (ICC). A second rater proficient in phonetic transcription and trained in phonological analysis transcribed and scored 100% of the baseline, probe, and follow-up nonword naming trials. The analysis yielded an ICC of .965 for C.N. and .974 for U.P., indicating excellent interrater reliability. Given the nature of K.T.'s language presentation, phonological analysis was not completed as he did not approximate targets.

Transcription reliability was completed for a random sample (20% of transcripts for C.N. and U.P.). Point-by-point word-level reliability (total agreements/total possible agreements) was .897 for C.N. and .950 for U.P. Point-by-point coding reliability was completed for 20% of discourse transcripts (total agreed upon CIUs/total possible). Reliability for C.N. was .870 and .880 for U.P. Point-by-point coding reliability was completed for 30% of discourse transcripts for C.N. for percent agreement for verbs, closed class words, and sentences as determined by total agreed upon/total possible. Reliability was .941 for verbs, .873 for closed class words, and .935 for sentences.

Results for cognitive-linguistic measures

Results for K.T.

Success in word learning practice

K.T.'s receptive learning in the trained task increased from 0.20 correct at baseline to 0.70 at 48-hr posttesting ($p = .004$; Figure 4A) of a possible 20 items. K.T.'s expressive learning was not examined using phonological analysis, because he frequently produced neologisms and did not approximate targets. Although no items were learned expressively, K.T. consistently repeated an incorrect novel name across sessions for many of the items (/flapflap/ for "duniseb").

Language outcome measures

K.T.'s verbal word span improved significantly posttraining ($p < .001$). Some language measures improved, but the changes were not found to be significant (Table 2). K.T.'s raw score on the PPVT increased from 124 to 168, with an improved standard score of 68 to 79, increasing from between 1 and 2 standard deviations (*SD*s) below average to less than 1 *SD* below average. Naming on the PNT improved using a lenient scoring (name produced anywhere in the response) but was not significant. All other measures, including the test of new word (alien names) learning ability and discourse, did not significantly change.

New word learning (single-session task)

K.T. was enrolled in the treatment protocol before we added Version 2 of the test of new word learning to assess the ability to learn novel words. Thus, he received only the first version of the single-session alien word learning measure.

Control tasks

There were no significant changes in K.T.'s performance on the verbal control task (PALPA oral reading of regular and exception words) or the nonverbal control task (Five-Point Test).

Results for U.P.

Success in word learning practice

U.P.'s receptive and expressive learning from baseline to 48-hr posttesting is depicted in Figure 4B. Receptive learning increased from a proportion of 0.20 correct at baseline to 1.00 correct at 48-hr posttesting ($p \leq .001$). Expressively, at 48-hr posttesting, he accurately named 0.15 of the trained items in entirety ($p = .231$). A phonological analysis was conducted to determine the average proportion of phonemes produced correctly in each session. This analysis included only target-related attempts and correct responses, as defined according to the following criteria: (1) included the initial phoneme + vowel and maintained the target syllable structure, (2) included the stressed vowel and maintained the syllable structure, or (3) included 50% or more of the target phonemes (e.g., /keɪbimap/ for Kibamop/kaɪbeɪmɑp/). U.P. approximated 10 out of 20 items (50%) and produced a proportion of 0.66 phonemes correct (Figure 5). Further examination of the items approximated at the final test revealed that U.P. learned, at least in part, a sample of items of each syllable length. See Supplemental Digital Content Appendix D (available at: http://links.lww.com/TLD/A64) for target items and responses.

Language outcome measures

U.P.'s pre- and posttraining results on all language outcome measures are presented in

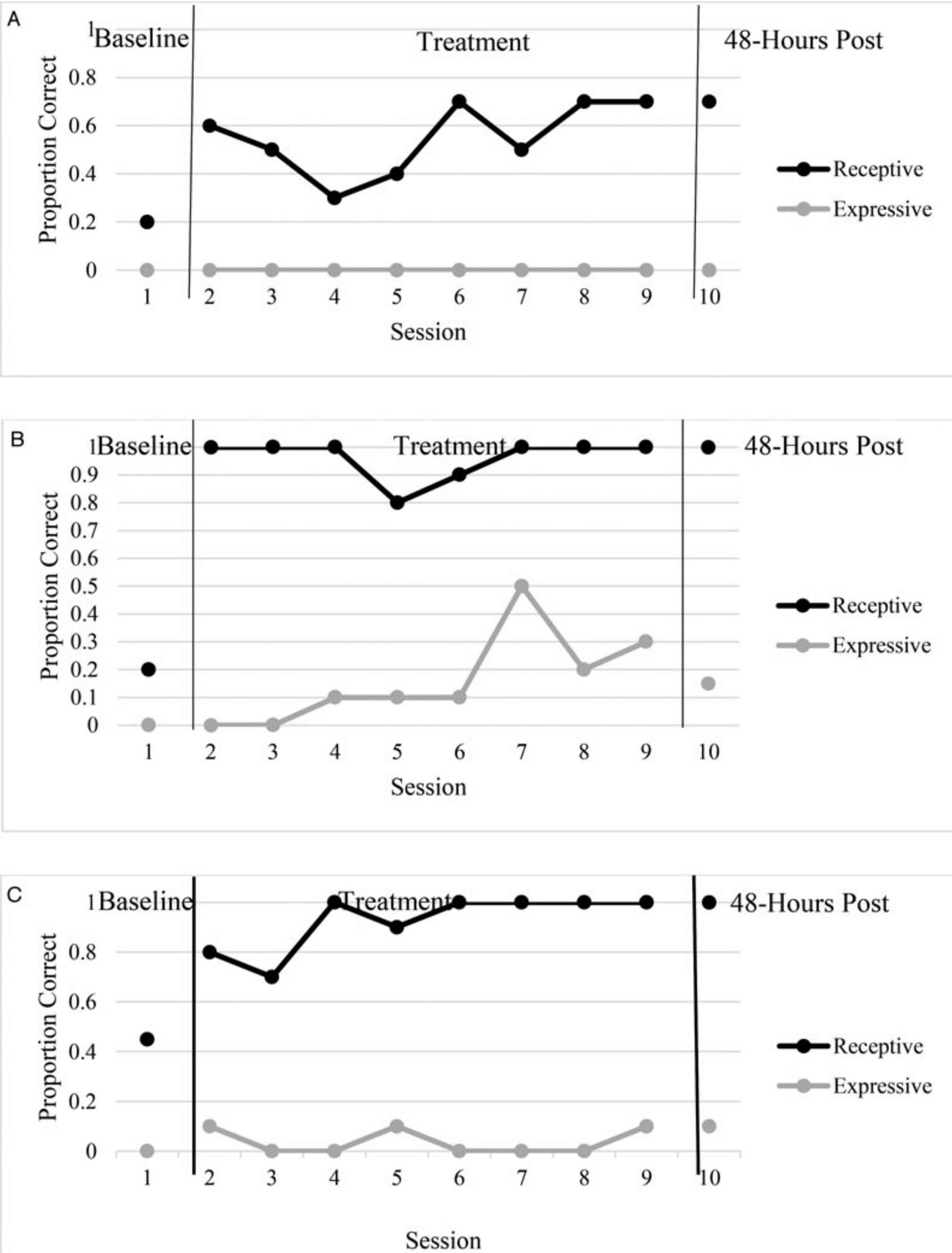

Figure 4. Proportion of items correct for items learned receptively and expressively. (A) K.T.'s proportion of items correct for receptive and expressive learning at baseline, Probes 1–8, and 48-hr posttesting during treatment. (B) U.P.'s learning at baseline, Probes 1–8, and 48-hr posttesting during treatment. (C) C.N.'s learning at baseline, Probes 1–8, and 48-hr posttesting during treatment.

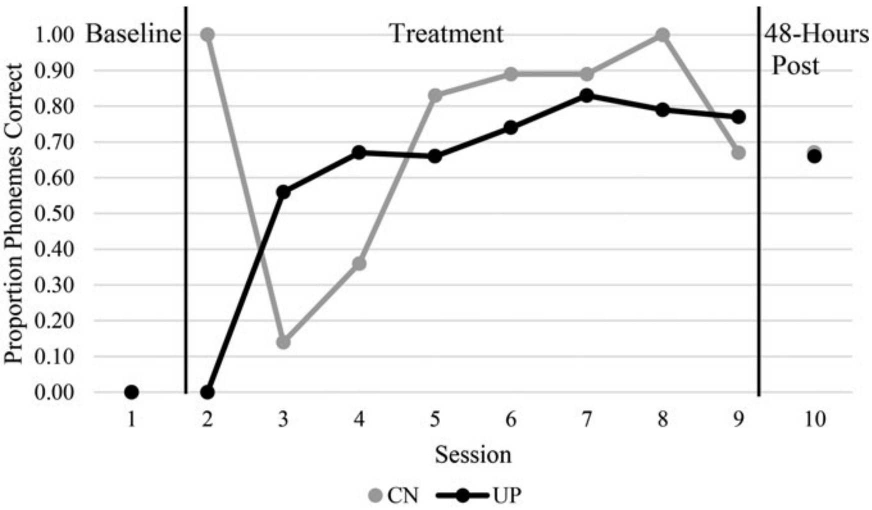

Figure 5. U.P.'s and C.N.'s expressive learning of novel items across treatment presented as proportions of phonemes correct from baseline, during treatment, and at 48-hr posttesting. Responses include correct responses as well as target attempts (excluding nonresponses and perseverations).

Table 2. He demonstrated significant improvement on digit span (digit repetition in serial order: $p \leq .001$; in any order: $p = .0495$; digit pointing ISO: $p = .028$).

On Nicholas and Brookshire's (1993) narratives, U.P. demonstrated meaningful improvement on the rate of CIUs after training. The rate of CIUs after training averaged over all 10 narratives was 0.69, which compared with his 0.58 rate of CIUs before training was greater than the benchmark of twice the SEM of 4.2% established by Brookshire and Nicholas (1994). These results are shown in Table 3.

Table 3. Average change in rate of CIUs in Nicholas and Brookshire's (1993) narratives

U.P.		C.N.	
Pre-Tx	**Post-Tx**	**Pre-Tx**	**Post-Tx**
0.58	0.69[a]	0.70	0.57[a]

Note. CIU = correct information unit; Tx = treatment.
[a]Denotes meaningful change in CIUs from pre- to posttraining. Meaningful change is defined by Brookshire and Nicholas (1994) as twice the standard error of measurement for change in rates of CIUs between two samples.

New word learning (single-session task)

Table 2 shows that U.P.'s receptive learning was quite good, but expressive learning was poor, as the rate of learned words was quite low. However, the specific measure of the proportion of phonemes produced correctly indicates some improved approximation of the target names. The proportion of correct phonemes produced on Version I of the alien word learning measure improved significantly from 0.24 before training to 0.41 ($p = .045$) after training, suggesting improved production abilities. However, the difference in the proportion of correct phonemes between pretraining Version 1 and posttraining Version 2 was not significant. This suggests that some improvement on Version 1 of the alien word learning measure could be attributed to its prior exposure before training.

Control tasks

U.P. showed no significant changes on the verbal control task (PALPA oral reading of regular and exception words) or the nonverbal control task (Five-Point Test).

Results for C.N.

Success in word learning practice

C.N.'s receptive and expressive learning from baseline to 48-hr posttesting is depicted in Figure 4C. Receptive learning increased to 1.00 proportion correct by Session 4 and was maintained at 48-hr posttesting ($p \leq .001$). Expressive learning showed minimal change across training, as he intermittently produced 0.10 of the items correctly and maintained this level of accuracy at 48-hr posttesting, which was not significantly different from baseline. As with U.P., phonological analysis was conducted to determine the average proportion of correct phonemes (Figure 5). Again, only target-related attempts as defined earlier were analyzed. At 48-hr posttesting, C.N. produced a proportion of 0.67 phonemes correctly (Figure 5). Across training, he appeared to show increased production of bi- and trisyllabic targets compared with monosyllabic targets. The target items produced across all sessions with their responses are provided in Supplemental Digital Content Appendix E (available at: http://links.lww.com/TLD/A65).

Language outcome measures

C.N.'s pre- and posttraining performance on all language outcome measures is presented in Table 2. Nonword and word repetition spans, used to measure verbal STM, increased significantly posttraining. For nonword spans, this improvement was for items recalled in serial order ($p = .009$) and for word spans items recalled in any order ($p = .025$).

On Nicholas and Brookshire's (1993) narratives, C.N. showed an increase in the proportion of CIUs in only one narrative ("Tell me about where you live"). His rate of CIUs declined in all other narratives, and his overall average change from 0.70 to 0.57 was greater than the benchmark of twice the SEM of 4.2% established by Brookshire and Nicholas (1994). Thus, he demonstrated a meaningful decline overall on this narrative discourse measure according to the criteria of Brookshire and Nicholas (1994). Table 3 shows the changes in the average rate of CIUs before and after training.

Table 4 shows that the average proportion of closed class words did not change significantly across all narratives. All other measures, including the average proportion of verbs and sentences as well as single-word measures, did not significantly change (Tables 2–4).

New word learning (single-session task)

No significant changes were observed for C.N. on the alien word learning measure.

Control tasks

No significant changes were observed in the verbal control task (PALPA oral reading of regular and exception words) and nonverbal control task (Five-Point Test).

Results for the analysis of white matter tracts (Tractotron and Disconnectome maps)

Figure 2 depicts detailed structural anatomical images for each participant. Figure 6 shows the overlap between the lesion of each

Table 4. C.N.'s average proportions for complex grammatical forms[a]

	Proportion Closed Class Words		Proportion Verbs		Proportion Sentences	
	Pre-Tx	Post-Tx	Pre-Tx	Post-Tx	Pre-Tx	Post-Tx
Average of narratives	0.22	0.27	0.32	0.29	0.30	0.30

Note. Tx = treatment.
[a]Significance at $p < .05$, calculated using Tests of Difference Between Proportions.

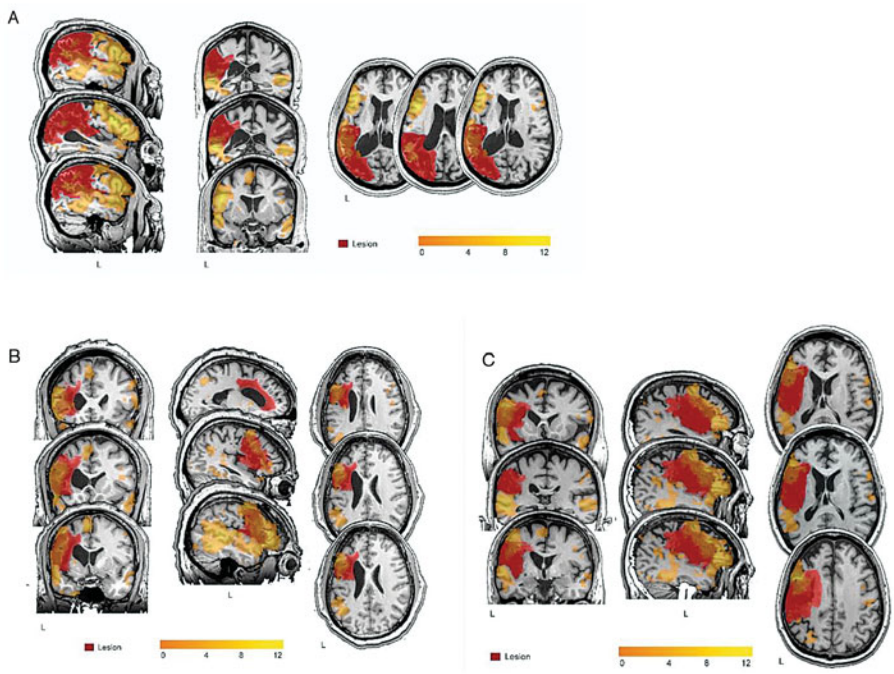

Figure 6. T1-weighted normalized images of each participant's area of infarct in which lesion localization (mask) is presented in red. Overlapped is shown the activation of the NeuroSynth fMRI meta-analysis results on the term "language" (*yellow-orange colors*). (A) K.T.'s lesion. (B) U.P.'s lesion. And (C) C.N.'s lesion.

participant and results of meta-analysis of language activation fMRI studies (revealing standard activations for language processing in functional language networks). Each participant's T1-weighted image underwent lesion-based disconnection analysis using Tractotron for obtaining the proportion of damage of dorsal and ventral tracks affected by the lesion. Figure 7 shows the overall overlap between each lesion area and the three segments of the AF (dorsal pathway). Finally, Figure 8 (left panel) depicts the overlap between the lesion mask and the overall AF (considering the sum of the anterior, posterior, and long AF segments) and the ventral pathways (considering the sum of ILF, IFOF, and UF). Besides, Figure 8 (right panel) shows the Disconnectome maps that reveal distant areas possibly affected by the lesion for each participant, overlaid on the dorsal and ventral pathways (see Table 5 for the Tractotron results on the proportion of disconnection or damage for each track).

For the AF segments, the overall proportion of damage for K.T. was nearly 49% (see Table 5), especially affecting the anterior and posterior segments. In comparison, the proportion of AF disconnection for U.P. was only 15%, with the posterior parietotemporal segment being the most well-preserved part. C.N. was also largely affected (overall proportion of damage 47%), but the largest disconnection was for the anterior and long segments and the posterior segment was better preserved (Table 5; see Figures 7 and 8A). Thus, U.P. was the participant who presented with the best preservation of the AF.

The results for the ventral pathways for K.T. (Table 5) showed partial damage overall (15%), with IFOF and ILF being partially disconnected (Figures 8A and 8b). This is probably due to the lesion affecting more posterior temporal, parietal, and occipital regions that had spared the UF track. Participant U.P. also showed well-preserved ventral pathway

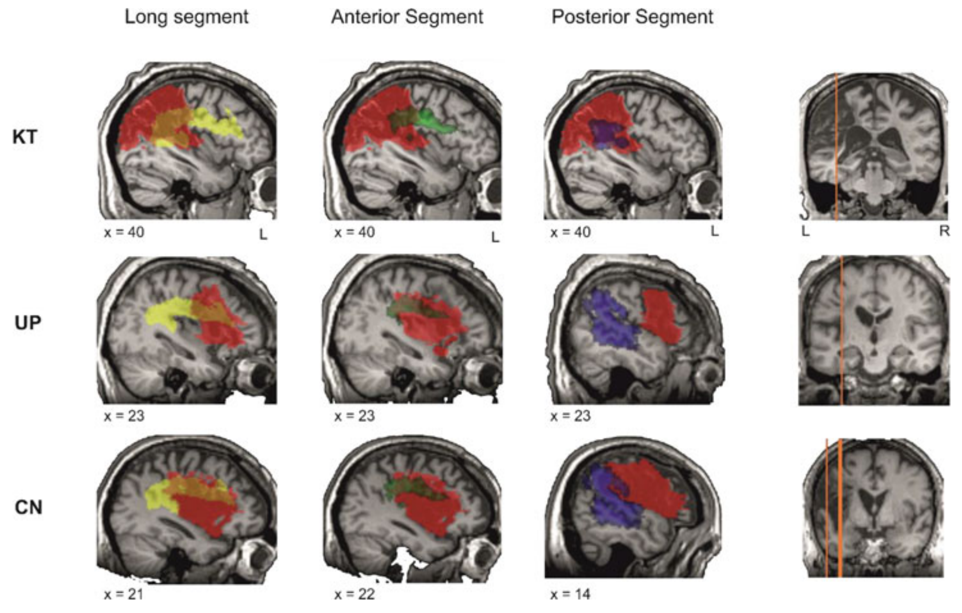

Figure 7. Track-wise analysis showing the overlap between lesion area (red mask) and the probability templates for the three segments of the AF (long—yellow; anterior—green; and posterior—blue; extracted from the Tractotron atlas and thresholded at 70%). Results are overlaid over the T1-weighted image in MNI space. AF = arcuate fasciculus; IFOF = inferior fronto-occipital fasciculus; ILF = inferior longitudinal fasciculus; UF = uncinate fasciculus.

connectivity (the proportion of disconnection overall was 12%), with UF and IFOF (at the vicinity of the insular cortex) being only partially affected and ILF appearing intact (see Table 5). Finally, C.N.'s ventral pathways were not much affected as his overall proportion of disconnection was about 5% (Figure 8B; Table 5).

DISCUSSION

The present study addressed two hitherto unexplored issues in word learning in aphasia, namely, the use of novel word learning as a means to stimulate impaired verbal STM and language system, and the role of a central language pathway (AF) in word learning success in aphasia. Our hypothesis was that a demanding repeated practice with novel word learning could increase the efficacy of related cognitive-linguistic and memory systems. Thus, we first determined whether our three PWA could learn novel items expressively and/or receptively and how repeated practice in a novel word learning task might impact language, verbal STM, and single-session word learning measures. Second, we evaluated whether the structural integrity of the dorsal language pathway (AF), believed to be integral for word learning, was related to word learning outcomes in our three PWA.

The results of this study are discussed in more detail later, but they should be considered as preliminary, given our current sample and the overall study design. To summarize, we found that on the training task, improvement in receptive word learning was more robust than expressive learning (replicating results from other novel word learning studies (e.g., Gupta et al., 2006). Regarding verbal span, each participant showed improvement on at least one of the verbal span measures. In addition, there was improvement on the language outcome measures but not the control tasks. One participant whose aphasia was mild and whose left AF and temporoparietal connections were relatively spared compared with the other two participants demonstrated

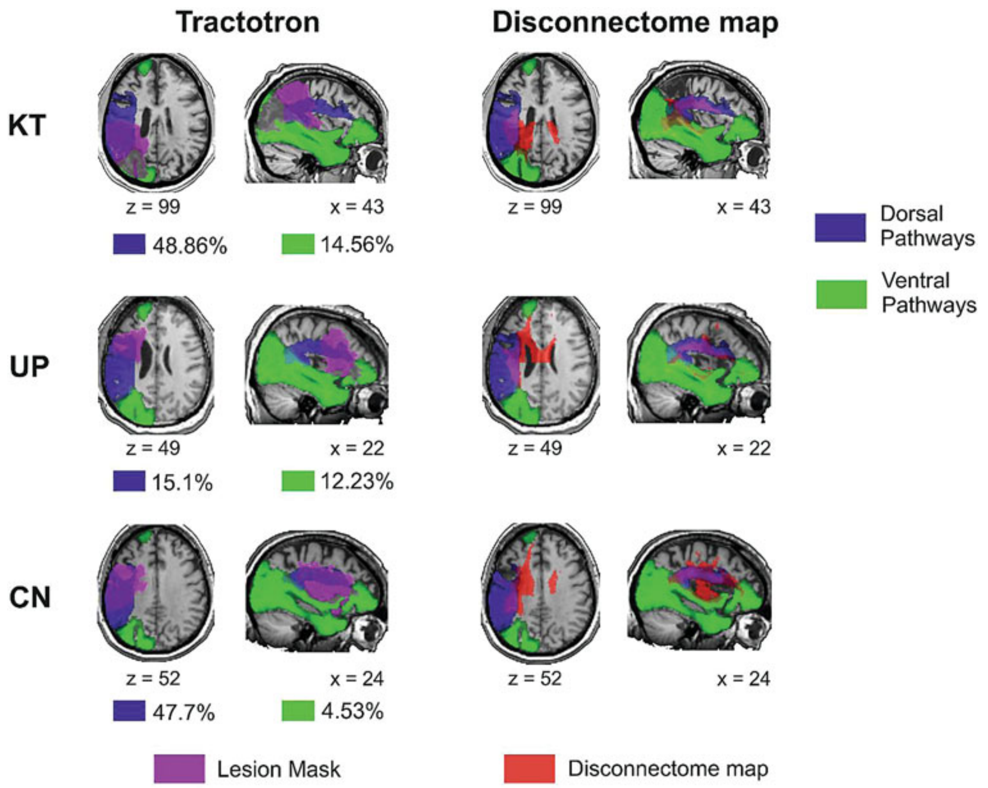

Figure 8. Lesion-based disconnection analysis. At the left column, we show the overlap between lesion mask (overlaid over the T1-weighted image in MNI space of each patient) and the dorsal (displayed in blue) and ventral pathways (displayed in green). Probabilistic templates of the dorsal pathways correspond to the sum of all AF branches and the ventral one corresponds to the sum of the IFOF, ILF, and UF white matter templates (using Tractotron white matter atlas and thresholded at 70%: Only voxels having a 70% probability of being part of the pathways according to the atlas are shown). Notice that overall proportion of disconnection for dorsal (blue) and ventral (green) pathways is displayed at the bottom for each patient. At the right side, we depicted the overlap between each patient Disconnectome map (red) and the same dorsal and ventral templates (obtained from http://toolkit.bcblab.com). AF = arcuate fasciculus; IFOF = inferior fronto-occipital fasciculus; ILF = inferior longitudinal fasciculus; UF = uncinate fasciculus.

better new word learning. In the following text, we discuss the outcomes of this study in the context of other studies of novel word learning and then the results for each of the three participants of this study. The clinical relevance of the data from this study is then considered and some potential future directions of this line of research are noted.

Learning and language outcomes

Previous research on word learning in aphasia (Kohen, Sola, Tuomiranta, Laine, & Martin, 2012; Martin et al., 2012; Peñaloza et al., 2014, 2016, 2017; Tuomiranta et al., 2012, 2013, 2014; Tuomiranta, Grönholm-Nyman, et al., 2011) has demonstrated variable degrees of receptive and/or expressive novel word learning in PWA. The present results are consistent with these findings. Furthermore, as hypothesized, we found that all participants showed improvements in verbal STM measures after the repeated novel word learning practice.

This study used repeated practice of novel word-referent associations with feedback as the basic word learning mechanism. Some

Table 5. Proportion of disconnection in white matter tracks, based on results from Tractotron

	Proportion of Disconnection							
	Dorsal Pathway (AF)				Ventral Pathways			
Patients	**AF Long Segment**	**AF Anterior Segment**	**AF Posterior Segment**	**Overall Dorsal**	**UF**	**IFOF**	**ILF**	**Overall Ventral**
K.T.	37.1%	43.5%	66%	48.9%	0%	20.7%	23%	14.6%
U.P.	22.3%	23.2%	0%	15.1%	22.6%	14.1%	0%	12.23%
C.N.	40.1%	90.6%	12.6%	47.7%	7.6%	6%	0%	4.53%

Note. AF = arcuate fasciculus; IFOF = inferior fronto-occipital fasciculus; ILF = inferior longitudinal fasciculus; UF = uncinate fasciculus.

studies have suggested adding strategies and techniques to improve learning of novel words in aphasia, such as identifying an individual's best input modality for word learning (Kohen et al., 2012; Tuomiranta, Rautakoski, Martin, & Laine, 2011) and pairing the novel item with semantic information (Kelly & Armstrong, 2009; Tuomiranta et al., 2012). Basso, Marangolo, Piras, and Galluzzi (2001) and Kelly and Armstrong (2009) have suggested that other modifications such as provision of orthographic or phonological cues may also aid learning. Finally, errorless learning also has been used to minimize production of errors that might become integrated into memory traces, with feedback or cueing added to increase learning (e.g., Fillingham, Hodgson, Sage, & Lambon Ralph, 2003; Middleton & Schwartz, 2012). In the present study, we used errorful learning coupled with feedback.

The three participants in this study presented with diverse language profiles, which might determine the learning strategies that may be useful for them. An understanding of each individual's language profile and brain structural connectivity profile may provide insight into their individual learning performances. In addition, building on the learning data and cognitive-linguistic outcome measures, the track-wise lesion analysis provides insight into the neural correlates of word learning and allows us to better understand the patterns of learning observed. As mentioned, the left AF has been implicated as a key component in novel word learning (López-Barroso et al., 2013). In the following text, we discuss the participants' novel word learning success and related STM/language outcomes in light of their language profile and the integrity of their left AF.

Success in word learning practice

K.T.'s word learning success

K.T. demonstrated moderate receptive learning and no expressive learning across training. Further analysis of his cognitive-linguistic background and lesion data help understand these results. K.T. presented with

Wernicke's aphasia and significant difficulties with auditory comprehension and repetition. It is worth mentioning that K.T. was the participant with the largest damage to the AF, especially concerning the proportion of disconnection of the posterior segment, as well as a more severe disconnection of ventral pathways (ILF and IFOF). Thus, K.T.'s dorsal pathway connectivity is affected by damage to much of the left parietal lobe and portions of the superior temporal gyrus, which also affects temporoparietal and parieto-occipital regions (see Figure 8). Damage to the inferior parietal lobe has been implicated in decreased or impaired speech repetition (Fridriksson et al., 2010). Parker et al. (2005) report that white matter connections between the inferior parietal lobe and other more classical speech areas are related to production and comprehension. Accordingly, it would be expected that K.T. would have difficulty with repetition (Fridriksson et al., 2013; Ivanova et al., 2016; Jang, 2013; Tak & Jang, 2014; Torres-Prioris et al., 2019), which would disrupt the relationship between nonword repetition and word learning (Gupta, 2003). K.T.'s poor performance on expressive word learning could be attributed to his repetition difficulty (limited digit and word span capacities), which might be related to severe damage to the posterior segment of the AF. This damage was not observed in the other two participants (for example, C.N.). It is noteworthy, however, that despite the severe damage to the AF pathway thought to be crucial for word learning, he learned a significant proportion of items receptively. This suggests that receptive learning may rely less heavily on this pathway but that other compensatory learning mechanisms could help in building new vocabulary, using preserved language networks (see as an example, Tuomiranta et al., 2013).

U.P.'s word learning success

U.P. learned items receptively with limited exposure, and expressively he approximated a number of items. U.P.'s aphasia was relatively mild, with good auditory comprehension and single-word repetition pretraining (Table 1). Kelly and Armstrong (2009) suggest that severity of language impairment may impact novel word learning. Consistent with this idea, U.P.'s relatively less severe aphasia could account for his gains in learning, as he reached ceiling-level performance on receptive learning during the second session and achieved the highest proportion of average phonemes correct. Should training have continued, U.P. might have demonstrated additional learning gains. U.P.'s repetition and digit span were on the high end of spans of PWA (between 3.6 and 4.8), which is consistent with the correlations between digit span, nonword repetition, and word learning reported by Gupta (2003). Nonetheless, U.P. demonstrated difficulty learning the novel items in their entirety, producing phonological errors for both vowels and consonants and confusing one item with another, although this is consistent with the novel word learning literature for those with aphasia (e.g., Gupta et al., 2006; Kelly & Armstrong, 2009). It is important to mention that compared with the other two participants, U.P. showed less severe disconnection to the AF with sparing of the posterior temporoparietal AF segment, which might explain his better repetition and expressive learning abilities. Because his ventral ILF pathway was also well preserved, U.P. could be using this posterior AF route to convey information to the temporal ventral pathways (ILF and IFOF), allowing a better cross talk between the dorsal and ventral routes. This increased transfer of information between the dorsal and ventral routes could provide important support to novel word learning, although this will require further investigation.

C.N.'s word learning success

C.N. was successful with receptive learning but much less so with expressive learning. He presented with intact auditory comprehension for single words and sentences but demonstrated some difficulty with repetition. C.N.'s medical records indicated the presence of apraxia of speech, which impacted his repetition. Therefore, similarly to K.T., at least some of C.N.'s difficulty in word learning could be attributed to his difficulty with single-word and sentence repetition (Gupta, 2003). C.N.'s lesion extended into the inferior parietal lobe and the angular gyrus as well as insular regions (see possible disconnection of white matter ventral tracks in Figure 8). Although the damage was not as severe as in K.T., this could account for some of his difficulty with repetition of nonwords and with expressive learning of novel words. However, C.N. demonstrated a high digit span, which may also have supported his learning (cf. Gupta, 2003). Also, like K.T., C.N. presented with considerable damage to the AF but a partially preserved posterior segment. Although the overall percentages of AF damage are similar for K.T. and C.N., their outcomes are different, with better expressive learning for C.N. than for K.T. This difference could be associated with the preservation of the posterior AF segment in C.N.

Altogether, the present evidence from the three participants suggests that the AF is an important component of word learning, although receptive learning and some expressive learning may occur despite significant damage to the different segments of this dorsal tract, possibly due to employment of preserved compensatory learning mechanisms (López-Barroso et al., 2011; Torres-Prioris et al., 2019; Tuomiranta et al., 2013).

Language outcome measures

In this analysis, we determined the impact of repeated novel word learning practice on various language outcomes. On the basis of Gupta's (2003) model relating word learning and language processing to verbal STM, we hypothesized that repeated practice with a new word learning task would provide stimulation that could elicit improvements in expressive and receptive language, as well as measures of verbal STM. This analysis was further motivated by neuroimaging studies, indicating that brain areas associated with verbal STM, such as left inferior parietal lobe, are activated by novel word learning tasks (Cornelissen et al., 2003; Laine & Salmelin, 2010; López-Barroso et al., 2015). A final motivation for this analysis comes from Dignam et al.'s (2016) study, which indicates a positive correlation between novel word learning ability with immediate posttherapy outcomes in anomia training. This finding concurs with the idea that learning ability could be targeted in therapy and result in gains in language abilities (Kelly & Armstrong, 2009; Tuomiranta et al., 2013).

K.T.'s language outcome measures

On span tasks, K.T. showed significant improvement on word repetition span. This was unexpected, as his lesion encompasses the majority of the left inferior parietal lobe, an area associated with verbal STM (Fridriksson et al., 2010). However, others have documented cases of compensatory neuronal activation, allowing for completion of tasks involving damaged brain regions (e.g. Torres-Prioris et al., 2019; Tuomiranta et al., 2013). We cannot make a claim for compensatory activation based on the data in this study, but this possibility is worth considering for future studies. Another potential explanation for K.T.'s span performance comes from Gupta's (2003) observation of correlations between nonword repetition, span, and learning. The learning task provided an opportunity to practice nonword repetition regularly and might have served as a means of "exercising" verbal STM in a manner that had not previously been explored.

Along with span, K.T.'s receptive and expressive language measures improved. Although primarily a descriptive measure, K.T.'s performance on the PPVT is noteworthy as there was a gain of almost 1 *SD* following the training exercise. K.T.'s receptive learning of novel words also increased, although auditory comprehension difficulty was evident throughout training. Although the other participants learned to identify the novel items by Session 2, K.T. identified only 0.70 items accurately by 48-hr posttesting. Nonetheless, given his overall language difficulty, we viewed this growth as a positive learning effect. In addition, although K.T. did not learn any items expressively, he named correctly (with lenient scoring) 11 additional items posttraining on the PNT (not statistically significant). Lenient scoring reveals some learning, as it indicates a correct response, but one that did not occur as the first initial response. As noted earlier, K.T. developed his own names for many of the items (some visually related and some neologisms) and he repeatedly recalled these names for certain items. It is conceivable that the repeated retrieval of his self-created item names reflected some learning. If future studies provide additional evidence that changes in language and verbal STM abilities could be attributed to the training provided, this would provide more support for our hypothesis that a novel word learning practice may improve lexical access via a verbal STM mechanism. K.T.'s improvement on both a span task and language outcome measures provides preliminary evidence that is worth investigating further.

U.P.'s language outcome measures

U.P. demonstrated significant posttraining improvement on digit span in both the repetition and pointing conditions. The improved digit span is consistent with Gupta's (2003) findings of a correlation with word learning. Interestingly, U.P. showed the greatest expressive learning of the three participants and was the only one who demonstrated a significant improvement in digit span in both conditions, supporting the hypothesis that new word learning engages verbal STM as measured by these span tasks.

Although no significant changes were observed for tests of single-word recognition or production, there was a significant change in the proportion of CIUs during narrative production. This positive outcome, coupled with the significant improvement on digit span, supports the hypothesis that new word learning benefits from engagement of verbal STM, which, in turn, supports lexical access. Interestingly, U.P. demonstrated the greatest level of expressive learning as well as a significant increase in the proportion of correct phonemes on the novel word learning pre- and posttesting (Version 1), indicating that he did learn throughout training.

C.N.'s language outcome measures

C.N. improved significantly on nonword repetition span and word repetition span. Along with the other two participants, this is consistent with Gupta's (2003) findings of a correlation between nonword repetition and word learning. C.N. showed some learning effects, suggesting that the learning task may have actively engaged verbal STM, as suggested for K.T. and U.P. Although data from three participants are not enough to claim this may occur in all PWA, they do demonstrate that those with diverse language profiles and severity may show some improvement in verbal STM as measured by digit and word spans following this training, as C.N. was the only nonfluent participant.

As with U.P., C.N.'s pretraining single-word production and auditory comprehension levels were close to ceiling, and no significant changes on these measures were expected. Regarding narrative production, although he showed some improvement on span tasks, on average, C.N.'s narratives showed a significantly lower percentage of CIUs.

In light of C.N.'s performance, it is important to acknowledge individual variability within aphasia and how this may impact performance (Dell, Schwartz, Martin, Saffran, & Gagnon, 1997). Production may be impacted by a variety of factors, such as fatigue and frustration (Dell et al., 1997). In retrospect, C.N. was experiencing frustration toward the end of training and into the posttesting period, as he knew he was having difficulty learning the items. Although this may not entirely explain his decreased rate of CIUs at posttraining, it may, in part, identify why his performance began to decline at this time. Given C.N.'s agrammatic presentation, structural analysis for closed class words, verbs, and sentences was completed only for this participant. As shown in the results, training did not yield significant results for these measures. With a profile consistent with nonfluent aphasia, his needs may have differed from those of K.T. and U.P. as well. Kelly and Armstrong (2009) suggest that training of novel verbs may be beneficial for those with symptoms of agrammatism, while the training presented included only training of novel nouns. Considering C.N.'s type of impairment, training of novel items associated with grammatical forms or actions may potentially lead to better retrieval of these forms in production.

Clinical implications

Recently, there has been considerable effort to address the need to "bridge the gap" between theories of language and cognition and clinical interventions for aphasia. The outcomes of this case series study exemplify the ways in which theory can inform practice. Cognitive and neural theories of language processing do not necessarily inform therapy (Ferguson, 1999) or the therapeutic relationship between the clinician and the client (Horton & Byng, 2000). Nonetheless, the American Speech-Language-Hearing Association's (2005) standard of evidence-based practice includes consideration of theoretical models of language. In that spirit, this study was motivated by a theory and evidence that verbal STM ability underlies repetition, recall, lexical retrieval, and verbal learning (Gupta, 2003; Gupta et al., 2006; Tuomiranta et al., 2012, 2013; Tuomiranta, Grönholm-Nyman, et al., 2011, Tuomiranta, Rautakoski, 2011), leading some to postulate a role of learning in training (Dignam et al., 2016; Kelly & Armstrong, 2009; Tuomiranta et al., 2013), although novel word learning has not been trialed as a method of treatment itself. We used a novel word learning task as a training paradigm to test this model that relates verbal STM abilities, word learning, and lexical access. We conclude that the results not only provide some preliminary support for this theoretical model but also inform models of treatment, providing insight into the roles of cognitive processes that contribute to learning and treatment outcomes.

Therapy can focus on functional communication, using techniques such as script training or self-cueing methods (Boyle & Coelho, 1995; Youmans, Youmans, & Hancock, 2011) or more direct impairment-based approaches. It is vital for treatment approaches to be based on theory and supported by evidence. Both of these elements are present in this evaluation of the potential contribution of a new word learning paradigm to better understand the involvement of verbal learning ability in treatment outcomes. Demonstrating that PWA can learn new words reveals preserved learning strategies that could be incorporated into treatments of word retrieval (Kelly & Armstrong, 2009; Tuomiranta et al., 2012, 2013).

Limitations of the study

Although this study provides some support for the hypothesis that novel word learning practice can have a role in aphasia treatment by engaging verbal STM, there are several limitations to be considered. First, the pre/posttest measure that could be considered as closest to the trained task, acquisition of alien names, did not show clear-cut improvement across the participants. One can speculate whether the difficulty level of this pre/posttest measure was optimal for the participants' varied language profiles. Second, the small number of participants cannot represent the wide variety of impairments and severity levels in PWA. Thus, replications with a larger and more diverse sample are needed to determine the benefit of this approach. Third, the experimental design could be improved. Multiple baseline design across individuals, with two or more baseline assessments of the outcome measures, would help rule out confounds of test–retest/learning effects on these measures. Concerning group studies, a randomized controlled trial would provide strongest evidence for the feasibility of our approach, albeit the great variability in aphasia symptoms and the limited access to suitable participants are issues here. Fourth, intrarater reliability was not completed for the phonological analysis. This measure would have been beneficial to ensure accurate and replicable transition as the measure of expressive language learning.

Future directions

Future studies of learning ability in aphasia might customize the learning to the needs and abilities of the participant, using strategies and cueing techniques that might further improve learning outcomes (Kelly & Armstrong, 2009). The effects of this nonword learning training could also be compared with a treatment utilizing real words that are less familiar, such as names of dog breeds (Freed, Marshall, & Nippold, 1995; Freed, Marshall, & Phillips, 1998). Finally, it would be interesting to include novel verbs, as this might be helpful in treating nonfluent clients.

CONCLUSIONS

The outcomes of the present study provide support for the theory of an underlying relationship between verbal STM and word learning. For many PWA, it would be beneficial to treat the underlying mechanisms of the language impairment and, if possible, impact change in more than one task. Engaging word learning systems in a treatment context may stimulate fundamental cognitive-linguistic processes (STM, lexical access) that support language ability and functional communication. The present study provides the first pieces of evidence in this direction.

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