

Links between short-term memory and word retrieval in aphasia

Irene Minkina
Temple University
Department of Communication Sciences and Disorders
iminkina@temple.edu

Nadine Martin
Temple University
Department of Communication Sciences and Disorders
nmartin@temple.edu

Kristie A. Spencer
University of Washington
Department of Speech and Hearing Sciences
kas@u.washington.edu

Diane L. Kendall
Veterans Affairs Medical Center Puget Sound
University of Washington
Department of Speech and Hearing Sciences
University of Pretoria
dkendall@u.washington.edu

Correspondence concerning this article should be addressed to Irene Minkina, Temple University, Weiss Hall Room 110, 1701 N. 13th St., Philadelphia, PA 19122

Email: iminkina@temple.edu

Abstract

Purpose: This study explored the relationship between anomia and verbal short-term memory in the context of an interactive activation language processing model.

Method: Twenty-four individuals with aphasia and reduced short-term memory spans (i.e., impaired immediate serial recall of words) completed a picture naming task and a word pair repetition task (a measure of verbal short-term memory). Correlations between verbal short-term memory and word retrieval errors made on the picture naming task were examined.

Results: A significant positive correlation between naming accuracy and verbal span length was found. More intricate verbal STM analyses examined the relationship between picture naming error types (i.e., semantic versus phonological) and two measures of verbal short-term memory: 1) location of errors on the word pair repetition task and 2) imageability and frequency effects on the word pair repetition task. Results indicated that as phonological word retrieval errors (relative to semantic) increase, bias towards correct repetition of high imageability words increases.

Conclusions: Results suggest that word retrieval and verbal short-term memory tasks likely rely on a partially shared temporary linguistic activation process.

Aphasia, an acquired language disorder, impacts over a million stroke and head injury survivors in the United States (National Institute of Neurological Disorders and Stroke, 2015) and affects all linguistic domains, including speaking, understanding, reading, and writing (Rosenbek, LaPointe, & Wertz, 1989). Most aphasiologists agree that aphasia results from impaired *access*: Linguistic elements are not wholly lost, but access to linguistic representations is disrupted (McNeil, Odell, & Tseng, 1991). Thus, investigations of language breakdown must take into account not only linguistic representations, but also the processes that facilitate their access. Theoretically, such investigations will help determine how linguistic representations are activated and selected during language production and comprehension. Clinically, investigations of linguistic processing mechanisms will help move beyond identifying what language tasks are disrupted to understanding *why* the disruption occurred, thereby helping to inform the development of assessments and treatment programs for people with aphasia.

The current study investigated mechanisms underlying word retrieval impairment (anomia), a ubiquitous and pervasive symptom of aphasia (Benson, 1988). One process that underlies language, including word retrieval, is verbal short-term memory (STM), the temporary activation of linguistic representations (Martin & Saffran, 1997). This definition is consistent with Cowan's embedded processes model (Cowan, 1988), which holds that the storage system that supports linguistic processing must be at least partly language-specific, and thus, views STM as heightened activation of existing knowledge from long-term memory. Consistent with this claim, neural evidence points to shared networks between tasks classically labeled as STM tasks (i.e., immediate serial recall of a sequence of digits or words) and classic language tasks (Cahana-Amitay & Albert, 2015). Verbal STM is a subcomponent of verbal working memory, which includes the temporary storage system (i.e., STM) and attentional functions that 1)

maintain activation of verbal information beyond the temporal limits of verbal STM and 2) manipulate information in verbal STM in the service of a given goal (e.g., repeating a list of words backwards requires temporary storage of the linguistic information *and* an attentional mechanism that enables the numbers to be recalled in reverse order) (Baddeley & Hitch, 1974; Unsworth & Engle, 2007; Wright & Fergadiotis, 2012). A note must be made on the choice to use the term STM rather than working memory to describe the process of interest in the current study. Though the complete isolation of the temporary storage system (i.e., STM) from the larger concept encompassing this system and additional attentional functions is likely impossible, a number of studies have demonstrated the theoretical and empirical validity for studying STM and working memory as separate constructs (for review, see Unsworth & Engle, 2007). Every linguistic task likely has at least a minimal attentional component; however, the focus of the present work is to investigate how the fleeting verbal STM process supports language and affects its breakdown in aphasia.

The verbal STM model at the heart of the present study, based on principles of Dell's two-stage interactive activation (IA) model of word retrieval (Dell, et al., 1997), offers a linguistically-specified view of STM. Dell's model consists of three levels of interactive linguistic nodes: semantic nodes that hold conceptual information, lemma nodes that hold grammatical knowledge, and phonological nodes that hold sound-level information. Nodes at neighboring levels are connected through excitatory, bidirectional connections. Word production occurs in two steps: 1) selection of a lemma node and 2) selection of that node's corresponding phonemes. In the production of *cat*, for example, semantic nodes (e.g., furry, four legs) are activated first, and these units activate the corresponding lemma node and semantically related lemmas (e.g., dog), which in turn activate corresponding phonemes. As soon as activation starts

to spread, it begins decaying to baseline but is replenished by feedback from nodes at subsequent levels (phoneme to lexical nodes and lexical to semantic nodes). The most highly activated lemma is selected, and sends activation to its phonemes, which are selected in the second stage. In the case of weak activation or overly rapid decay, word retrieval can fail, resulting in the selection of a more strongly activated alternative (e.g., a semantic neighbor such as *dog*, a phonological neighbor such as *mat*, an unrelated real or nonword) or an omission.

Martin's model is derived from this IA model, and views verbal STM as the temporary activation of linguistic knowledge needed to process language (Martin & Saffran, 1997). The goal of the present study is to test this model's hypothesis that classic STM tasks (i.e., immediate serial recall) and language tasks (e.g., picture naming) rely on a shared temporary linguistic activation mechanism. This idea conflicts with Baddeley's classic model of working memory, which views verbal STM as a largely phonological process that is not intrinsically connected to language production and comprehension (Baddeley & Hitch, 1974). In Baddeley's model, a phonological store (i.e., verbal STM) temporarily holds verbal information (e.g., a sequence of words) via a phonological code and works with attentional mechanisms to retain and manipulate this information. These STM and attentional mechanisms compose the larger working memory system. A number of recent studies have continued to use Baddeley's phonological store to conceptualize verbal STM (e.g., Lauro, Reis, Cohen, Cecchetto, & Papagno, 2010; Schuchardt, Maehler, & Hasselhorn, 2011). Conversely, Martin's model views STM and language as intricately tied constructs, and argues that verbal STM makes use of a variety of linguistic codes (e.g., semantic, lexical, phonological) that are contingent on the needs of a given linguistic task. Though Baddeley (2000) amended the classic model (Baddeley & Hitch, 1974) by including a multimodal temporary storage system capable of integrating various types of information (i.e.,

episodic buffer), the updated model does not specifically outline a mechanism through which lexical and semantic information is stored in verbal STM.

STM: Methods of Study and Pertinent Research

In an immediate serial recall task, an individual hears a sequence of digits or words and repeats them in the same order (see Madigan, 1980 for a review). The capacity limit for recall of verbal information in typical speakers hovers around seven, give or take two items (Mathy & Feldman, 2012; Miller, 1956). The tendency to better remember the first few (*primacy bias*) and last few items (*recency bias*) than items in the middle of a list has repeatedly been observed, and Baddeley and Hitch (1974) attributed recency to enhanced availability of the last few items in the phonological store and primacy to subvocal rehearsal of the first few items. Martin and Saffran (1997) later amended these assumptions by incorporating lexical-semantic in addition to phonological knowledge as a partial explanation for these biases. The idea that lexical-semantic information facilitates the storage of verbal information in STM is supported by various findings, including the better recall of words over nonwords (Hulme, Maughan, & Brown, 1991), digits over words (Brener, 1940), high over low imageability words (Bourassa & Besner, 1994), high over low frequency words (Allen & Hulme, 2006; Roodenrys, Hulme, Lethbridge, Hinton, & Nimmo, 2002), concrete over abstract words (Allen & Hulme, 2006; Brener, 1940), and content over function words (Bourassa & Besner, 1994; Brener, 1940).

Studies have consistently demonstrated reduced verbal spans in individuals with aphasia relative to neurologically healthy individuals (e.g., Albert, 1976; De Renzi & Nichelli, 1975; Martin & Ayala, 2004; Martin & Saffran, 1997; Potagas, Kasselimis, & Evdokimidis, 2011) and individuals with brain damage without aphasia (Lang & Quitz, 2012; Laures-Gore, Marshall, & Verner, 2011; Kasselimis, et al., 2013). Additionally, correlational studies have demonstrated

that as verbal STM span length increases, so does performance on classic language tasks, such as word-to-picture matching and phoneme discrimination (Martin & Ayala, 2004; Martin & Gupta, 2004; Potagas, et al., 2011). Together, these findings demonstrate that verbal STM impairments in individuals with aphasia are not simply the result of generalized slow processing, but that verbal STM and language are likely subserved by overlapping neural networks.

Beyond Span Length: Mechanisms Underlying the STM-Language Link

Several studies of individuals with aphasia have made connections between error location (i.e., primacy and recency effects in repetition) and language processing. This notion was most strongly supported by a study of 15 individuals with aphasia by Martin and Saffran (1997), who predicted that individuals with aphasia who demonstrate greater impairments on *phonological* input processing tasks (e.g., phoneme discrimination) relative to lexical-semantic processing should be more accurate in retrieving *earlier* segments during a word span task (primacy bias). This prediction was rooted in an IA model: the earlier segments' activation has more time to spread to semantics prior to recall. However, those who demonstrated greater impairment on *semantic* input processing tasks (e.g., synonymy judgments) should be more accurate in retrieving *later* segments, which are supported via phonological activation but have not yet built up strong semantic activation (recency bias). Correlations between error location (primacy/recency biases) and language processing impairment type (lexical-semantic versus phonological) were consistent with the predictions, and similar results were found in a later study (Martin, Ayala, & Saffran, 2002). Additionally, Martin & Saffran (1997) predicted that individuals with greater impairments in phonological processing should demonstrate typical word imageability effects (believed to be tied to semantic processing; e.g., Martín-Loeches, Hinojosa, Fernandez-Frias, & Rubia, 2001; Nickels & Howard, 1994) and frequency effects

(believed to be tied to lexical processing; e.g., Goldrick & Rapp, 2007; Schilling, Rayner, & Chumbley, 1998) on the word span task because they would likely rely heavily on lexical-semantic processing to complete the task. These effects should, however, be diminished in individuals with greater lexical-semantic impairments who are likely relying primarily on phonology during the word span task. Correlations between word imageability/frequency biases and language impairment type were consistent with the predictions, though the correlation between frequency bias and language impairment type did not reach significance.

More recently, Wilshire, Keall, and O'Donnell (2010) conducted a case study of two patients demonstrating that the aforementioned findings may extend to word production. Patient TV demonstrated primarily phonological nonword naming errors, a primacy effect in serial recall tasks, and an imageability effect on serial recall. Patient NP demonstrated primarily semantic naming errors, a recency effect on serial recall, and no imageability effect. These results warrant further investigation of the relationship between word production and verbal STM breakdown.

Extant literature supports the idea that the STM system that supports language is domain specific, meaning that it does not support the recall of nonverbal information. The use of a Corsi Block Span Task (De Renzi & Nichelli, 1975), a spatial STM task which requires individuals to replicate sequences of blocks by pointing to them in order of presentation, with individuals with aphasia, has revealed conflicting findings regarding domain-specificity of STM. Though many individuals demonstrate stronger spatial span performance relative to verbal span, some individuals still show reduced spatial span in comparison to neurologically healthy controls (Martin & Ayala, 2004) and left hemisphere brain damaged adults without aphasia (Kasselimis, et al., 2013). Potagas et al. (2011) argued for a domain-independent STM on the basis of a correlation between the Corsi Block Task and classic language tests, but the concurrent finding

that digit span length also correlated with the language tests but not with the Corsi Block Task is problematic for this view. Martin and Ayala (2004) also demonstrated equivocal results. Digit and word repetition spans correlated positively with the Corsi Block Task in a group of individuals with aphasia, while pointing versions of the digit and word span tasks that require participants to point to numbers or pictures corresponding to the sequence they heard did not significantly correlate with the Corsi Block Task. Additional investigations are needed to determine whether and to what extent a domain-specific STM mechanism supports language.

Research Questions and Predictions

The goal of the current study was to investigate the relationship between verbal STM and word retrieval impairment type in individuals with aphasia through an analysis of errors occurring in word pair repetition and picture naming. The research questions were as follows:

- 1) Is verbal STM span length associated with 1) word retrieval accuracy and 2) a nonlinguistic (i.e., spatial) STM task? *Predictions:* Verbal STM span length will positively correlate with word retrieval accuracy but will *not* significantly correlate with spatial STM span length.
- 2) Is word retrieval impairment type associated with primacy/recency biases observed in a verbal STM task? *Prediction:* As phonological nonword naming errors relative to semantic errors increase, primacy bias will increase.
- 3) Is word retrieval impairment type associated with imageability and frequency biases observed in a verbal STM task? *Prediction:* As phonological nonword naming errors relative to semantic errors increase, imageability and frequency biases will increase.

Method

This project was approved by the University of Washington Institutional Review Board (IRB #48385), and informed consent was obtained from each participant.

Inclusionary Criteria

Twenty-four individuals with aphasia participated in this study (Table 1). All participants had left hemisphere damage due to a cerebrovascular accident (CVA), which was confirmed through a CT or MRI scan and interpreted by a radiologist or behavioral neurologist. Individuals with multiple left hemisphere strokes were included. Other inclusionary criteria were as follows: ≥ 6 months post CVA, ≥ 12 years of schooling, and between the ages of 30 and 70. All participants had to be native speakers or use English as their predominant language following stroke, confirmed by a short interview with participants and their caregivers. While right handedness was preferred, left handed individuals who presented with aphasia were included.

All inclusionary and descriptive language and verbal STM test scores are listed in Table 2. To confirm presence of aphasia, Comprehension of Spoken Language and Naming modality subscores of the Comprehensive Aphasia Test (CAT; Swinburn, Porter, & Howard, 2004) were calculated. Individuals who were below the cut-off scores ($\leq 56/66$ on Comprehension of Spoken Language and ≤ 69 on the Naming Subtest) met the language criteria. Additionally, individuals who did not meet one or both cut-off scores but demonstrated marked production and comprehension difficulties in conversation, during discourse testing (as measured by the CAT Picture Description), and during the rest of the language battery (including the Repetition subtest of the CAT), as confirmed by a certified speech-language pathologist, were also included. The 7 participants who did not meet the standard cut-offs all demonstrated marked anomia and slow,

Table 1. *Participant Demographic Characteristics*

ID	Sex	Age	MPO	Lang 1	Hand	Edu	Etiology	AOS characteristics
1	M	70	107	Eng	L	19	Remote left temporofrontal infarct w/ associated encephalomalacia	None
2	F	64	120	Eng	R	18	Left frontal, temporal, parietal infarct, prior to aneurysm clipping of left MCA (Hemorrhage, craniotomy x 2).	None
3	M	54	74	Eng	R	16	Small left cortical lateral frontal infarct	None
4	M	68	36	Eng	R	12	Left MCA infarct. Temporal lobe, insula, frontal, and parietal lobes affected.	None
5	F	71	125	Eng	R	14	Left MCA infarct involving basal ganglia and cortical grey matter	None
6	F	60	70	Eng	R	12	Large left infarct with involvement of temporal pole and frontal lobe (extending from orbitofrontal cortex to Broca's area and to superior frontal sulcus).	None
7	M	61	77	Eng	R	16	Left hemorrhage with involvement of basal ganglia, posterior frontal, temporal, and parietal lobes.	None
8	F	45	10	Eng	R	16	Left MCA infarct involving insula, operculum, modest extent of superior temporal gyrus, and extensive frontal cortex	None
9	F	54	54	Eng	R	14	Left MCA aneurysmal subarachnoid hemorrhage	Moderate. Slowed rate, segmented speech, increased difficulty on consonant clusters; presence of schwas and distorted substitutions
10	M	66	60	Eng	R	16	Left MCA involving anterior left parietal lobe extending to the level of the sylvan fissure with question of component of extension into the left temporal lobe. Mild effacement upon left lateral ventricle.	None
11	F	59	51	Eng	R	20	Decompressive craniotomy after large left CVA. Left internal carotid occlusion (likely a very large ischemic infarct s/p decompressive craniotomy).	None
12	M	72	64	Eng	R	23	Left hemorrhagic CVA with involvement of basal ganglia, adjacent insular cortex, left corona radiata, with ischemic damage to frontal lobe	Mild. Slightly abnormal rate; mild disruption to prosody and articulation
13	F	51	69	Gujarati	R	12	Left basal ganglia hemorrhagic infarct, with ischemic damage to overlying perisylvian cortex	None

14	M	61	116	Eng	R	19	Left MCA infarct, large territory hypodensity involving the left cerebral hemisphere in the frontal, temporal, and parietal lobes.	Moderate. Distorted substitutions, errors increase with increasing word length, abnormal prosody
15	F	71	41	Eng	R	14	Surgery to "tie off" aneurysm led to bleeding that required a 2nd surgery. Distal left M1 embolic event. Infarct involves part of putamen, insula, operculum (though minimal frontal), and extensive temporal and parietal lobe.	None
16	F	70	85	Eng	R	12	History of two strokes (or one stroke and 1 TIA). Left MCA territory infarcts including the temporoparietal junction, coronal radiata, and subinsular region (ischemic).	None
17	M	62	42	Eng	R	13	Distal L M1 event with extensive infarction of temporal lobe and insula and modest infarction of frontal and parietal operculum.	None
18	M	57	128	Eng	L	18	Large left MCA infarct with involvement in head of the caudate, most of left lenticular nucleus, the insular cortex, and posterior half of the left frontal lobe extending into the anterior portion of the left parietal lobe.	None
19	F	64	42	Eng	R	17	Large left basal ganglia hemorrhage with intraventricular extension.	None
20	M	60	32	Eng	R	16	Large left basal ganglia hemorrhage	None
21	M	70	59	Eng	R	16	Suggestion of subtle loss of gray-white matter differentiation in the left basal ganglia. Occlusive thrombosis within proximal aspect of left middle CVA.	None
22	F	72	34	Eng	R	16	Left M2 region infarct with loss of left insular ribbon, loss of gray white differentiation in the left frontal operculum and left parietotemporal lobes (ischemic).	Mild. Distorted substitutions, segmented syllables, increase in errors with increasing word length, slowed speech rate
23	F	56	17	Eng	R	12	Left MCA ischemic event. Infarct extending deep from lateral left frontal pole.	None
24	M	46	86	Eng	L	13	Massive left MCA infarct with subsequent surgical decompression. Left hemisphere is gone, expect for ACA and PCA territories.	None
<i>M</i>		61.83	66.63			15.56		
<i>SD</i>		8.04	33.77			2.95		

MPO = months post left CVA onset; Lang1 = native language; Edu = years of education; AOS = apraxia of speech

Table 2. *Inclusionary and Descriptive Short-Term Memory and Language Test Scores*

ID	Word Span	Corsi Block	RPM	CAT Naming				CAT Spoken Comprehension				CAT Repetition				CAT PD		
				Fluency	Obj.	Act.	Total	Words	Sent.	Par.	Total	Words	CW	NW	DS	Sent.	Total	Total
01	2.1	4	35	8	16	1	25	28	18	4	50	25	2	2	6	0	35	6
02	2	5	32	18	34	0	52	26	17	4	47	32	4	8	6	6	56	13.5
03	2.15	5	33	19	44	4	67	27	28	4	59	31	6	4	12	8	61	49
04	3.2	4	29	23	44	5	72	26	26	3	55	32	6	6	10	10	64	51
05	2.2	4	33	19	37	3	59	29	23	3	55	24	4	0	8	6	42	26
06	1.15	5	29	13	21	0	34	21	9	0	30	26	3	5	6	6	46	19.5
07	3.1	3	32	20	43	7	70	23	26	3	52	31	6	10	10	8	65	44
08	4	5	36	11	36	10	57	30	27	4	61	32	6	10	8	12	68	27
09	2.1	4	29	13	35	6	54	26	11	4	41	30	6	9	8	6	59	10
10	1.1	4	30	0	0	1	1	17	20	1	38	19	0	5	2	0	26	16
11	2.1	4	35	8	40	2	50	23	13	13	49	28	6	8	8	6	56	17.5
12	3.05	5	33	16	46	10	72	29	30	4	63	28	6	9	10	12	65	23
13	4.05	4	33	20	39	2	61	26	25	2	53	32	6	10	10	12	70	32.5
14	2.1	5	33	14	34	2	50	29	20	4	53	20	0	0	8	6	34	7.5
15	3.05	5	34	20	40	9	69	27	25	4	56	30	4	6	8	6	54	53
16	1	3	23	3	3	0	6	22	16	3	41	27	1	2	4	6	40	11
17	2.05	4	35	11	32	0	43	24	25	4	53	28	6	2	4	6	46	15.5
18	2	3	25	4	27	1	32	22	19	3	44	32	4	4	6	6	52	6
19	4	3	30	7	36	10	53	29	28	2	59	32	6	10	12	12	72	64.5
20	2	5	32	8	5	1	14	26	27	3	56	14	0	0	4	0	18	3.5
21	3.2	5	32	7	33	0	40	26	27	3	56	32	6	10	10	12	70	35
22	4	3	34	13	45	9	67	28	30	4	62	32	6	8	10	12	68	30.5
23	2.2	4	27	4	42	8	54	29	24	2	55	32	6	10	6	8	62	26
24	1.05	3	31	2	12	0	14	22	16	0	38	30	4	8	0	6	48	2
M	2.46	4.13	31.46	11.71	31	3.79	46.50	25.63	22.08	3.38	51.08	28.29	4.33	6.08	7.33	7.17	53.21	24.56
SD	0.96	0.80	3.23	6.66	13.98	3.80	21.46	3.25	6.04	2.39	8.54	4.86	2.20	3.59	3.05	3.73	14.82	17.42

CAT = Comprehensive Aphasia Test; PD = Picture Description; RPM = Raven's Progressive Matrices; CW = Complex Words; NW = Nonwords; DS = Digit Strings

halting, effortful speech in conversation and in the CAT picture description test, as well as slowed speed on formal and informal language comprehension tasks.

To confirm presence of verbal STM impairment, participants had to demonstrate impaired performance on a word pointing span task (Martin, 2012), which was selected over the repetition version because it does not require a verbal response, and may thus be a purer STM measure. Participants listened to a sequence of words and pointed to corresponding pictures in serial order. Each span length included 10 trials, and span length was calculated as follows: list length at which at least 50% of lists were reproduced correctly + .50 of the proportion of lists recalled at the next list length (Shelton, Martin, & Yaffee, 1992). Individuals with span lengths ≤ 4.0 met the verbal STM impairment criteria. Additionally, participants who achieved a score ≥ 4.1 (i.e., no more than 2/10 items correct on the 5 item list length) *and* a marked increase in difficulty at the 4 item list length (e.g., verbal report of increased effort/fatigue, significantly slowed response time, and/or a significant increase in omission of list items) were also included.

Exclusionary Criteria

Individuals with a history of right CVA, degenerative neurological illnesses, and/or currently untreated psychiatric illness were excluded. Individuals with a score below 23 on Raven's Progressive Matrices (Raven, Raven, & Court, 1998), a measure of non-linguistic processing impairments, were excluded. Additionally, individuals with visual impairment, as defined by failure to read the second-to-bottom line of the Tumbling E eye chart at a distance of 20 feet (D.F. Chang, 1995), and/or a hearing impairment, as defined by failure to pass an audiometric pure-tone, air conduction screening at HL 35 dB at 500, 1K, and 2K Hz for at least one ear, were excluded. A line bisection task was used to screen for visual neglect. Individuals with a severe apraxia of speech, as judged by an assessments of videos of participants'

performance on repetition, picture description, and other tasks from the CAT, were excluded.

Three certified speech-language pathologists evaluated the videos, and consensus judgments for the following behaviors were used: slow rate, prolonged segment durations and intersegment durations (including intrusive schwa), distortions, and prosodic abnormalities.

Classification of Word Retrieval and STM Impairments

The Philadelphia Naming Test (PNT; Roach, Schwartz, Martin, Grewal, & Brecher, 1996) was administered to determine word retrieval severity and the relative contributions of semantics and phonology to each individual's word retrieval impairment. The test is comprised of 175 nouns and provides thorough error coding guidelines based on Dell's IA model of word retrieval (Dell, et al., 1997). The PNT was presented on a computer with Microsoft Powerpoint 2010, and participants were instructed to name each black and white line drawing immediately using one word, with a limit of 30 seconds per picture. Participants' responses were audio recorded and scored offline by the first author or a research assistant trained in broad phonetic transcription. The first complete attempt, as defined by PNT instructions, was scored correct or incorrect, and incorrect responses were coded for error type according to PNT guidelines. The following distorted substitutions were scored correct in the 4 participants identified as mild-moderately apraxic: substitutions of voiced consonants for unvoiced, and vice versa, if place and manner were preserved, and substitutions of stop for nasal consonants, and vice versa, if place and voicing were preserved. Schwa insertions were also scored correct. These decisions were based on literature that argues that these errors are most likely motoric (Ballard, Granier, & Robin, 2000; Itoh, Sasanuma, & Ushijima, 1979; Mauszycki, Dromey, & Wambaugh, 2007; Odell, McNeil, Rosenbek, & Hunter, 1990). In order to classify word production impairment, a relative phonologic to semantic (P-S) index was calculated as follows: total # of phonologically

related nonword errors (P score) – total # of semantic errors (S score). To assess reliability, 15% of each participant's responses were randomly selected and coded by the same research assistant and another research assistant, and Cohen's Kappa (Landis & Koch, 1997) was calculated.

To quantify the nature of verbal STM impairment, 240 two- and three-syllable nouns were selected, and four lists of 60 words were created from this corpus: high frequency-high imageability, low frequency-high imageability, high frequency-low imageability, and low frequency-low imageability. Words were considered high frequency if they occurred more than 40 times per million and low frequency if they occurred less than 25 times per million (based on ratings from SUBTLEX-US database, Brysbaert & New, 2009). Words were considered high imageability if the imageability rating was greater than 497, and low imageability if the imageability rating was less than 497 (based on ratings from MRC psycholinguistic database, Coltheart, 1981) (Martin & Saffran, 1997). With the alpha criterion set at .05, the subsets of high and low imageability words did not differ in frequency, $t(238) = .031, p = .976$, and the subsets of high and low frequency words did not differ in imageability, $t(238) = .469, p = .640$. Phonotactic probability ratings were obtained from the Irvine Phonotactic Online Dictionary (Vaden, Halpin, & Hickok, 2009) to assure that high and low imageability words, $t(237) = -1.89, p = .060$, and high and low frequency words did not differ in phonotactic probability, $t(237) = .902, p = .368$.

Thirty word pairs were created from each of the four lists (120 total pairs). Words in each pair were matched for syllable length and were not semantically related. Words were recorded by a native male English speaker with a Marantz Professional Solid State Recorder, and recordings were spliced into word pairs separated by a silent 1 second interval. Word pairs were administered in two sets that contained the same pairs of items in different order, with a short

break between sets. The order of the sets and the word pairs within each set was randomized for each participant. Participants were instructed to repeat each word pair in serial order immediately after hearing it, and their responses were audio recorded with an Olympus Digital Voice Recorder. Recordings were transcribed by the first author or a research assistant, and each word was scored for whole word accuracy. Only first responses were scored, and responses initiated more than 5 seconds after the target was presented were not scored. All phonemes had to be produced accurately, and the word had to be produced in the correct serial position to be considered correct. If participants consistently repeated only the second word, it was considered to occur in the correct serial position, due to evidence that individuals who did this frequently were aware that they were omitting the first word (e.g., insertion of the word “blank” into the first word’s position). Distorted phonemes were scored correct, and modified scoring rules for individuals with AOS used for the PNT also applied to word pair repetition. Three bias scores were calculated for each participant: a primacy bias score ($\frac{\# \text{ first words correct}}{\# \text{ first} + \text{ second words correct}}$), an imageability bias score ($\frac{\# \text{ high imageability words correct}}{\text{total words correct}}$), and a frequency bias score ($\frac{\# \text{ high frequency words correct}}{\text{total words correct}}$).

To calculate nonverbal STM span, the Corsi Block Span Task (De Renzi & Nichelli, 1975) was administered. A participant’s nonverbal span was defined as one less than the length at which two consecutive trials (out of six total trials) were missed.

Data Analysis

For research question 1, word pointing span length was correlated with PNT accuracy and nonverbal span length. For research question 2, P-S scores were correlated with primacy bias scores. For research question 3, P-S scores were correlated with imageability and frequency bias scores. Correlation effect sizes were as follows: $r = .1$: small, $r = .3$: medium, $r = .5$: large (Cohen,

1988). Because these main analyses were based on a priori hypotheses and motivated by extant research, the alpha value for each of these analyses was set at .05 (2-tailed test). Contingent on findings of significant associations between bias scores (primacy, imageability, and frequency) and P-S scores, a multiple linear regression with simultaneous entry of bias score predictors was planned to determine whether each bias score was uniquely predictive of P-S score.

Results

Research Question 1: Word Retrieval, Word Pointing Span, and Spatial Span

Research question 1 investigated the domain-specificity of verbal STM by testing the relationship between word pointing span and 1) word retrieval accuracy and 2) nonverbal (spatial) span. Raw PNT accuracy scores are listed in Table 3. Pearson's r was computed to assess both relationships, and a large significant positive correlation consistent with the predictions was found between word pointing span length and word retrieval accuracy, $r(22) = .732, p < .001$, consistent with extant literature (Martin & Gupta, 2004). A post-hoc correlation between the Corsi Block Task and PNT accuracy was also performed, and no significant correlation was found, $r(22) = .13, p = 0.53$. Together, these findings demonstrate that verbal STM and word retrieval are strongly associated, and that this association is domain-specific.

Table 3. *Individual data: Verbal STM bias (primacy, imageability, and frequency) and word retrieval type scores*

ID	<i>Word Pair Repetition</i>					<i>Picture Naming (PNT)</i>			
	Word 1 Raw #	Word 2 Raw #	Primacy Bias	Image. Bias	Freq. Bias	Raw #	P score	S score	P-S Score
01	9	141	0.06	0.55	0.57	98	32	4	28
02	98	97	0.50	0.55	0.54	125	2	15	-13
03	171	93	0.65	0.60	0.56	160	4	9	-5
04	230	229	0.50	0.51	0.51	161	1	4	-3
05	100	62	0.62	0.71	0.58	152	7	3	4
06	138	5	0.97	0.54	0.53	68	18	14	4
07	198	185	0.52	0.54	0.55	143	5	16	-11
08	190	194	0.49	0.53	0.48	165	0	6	-6
09	156	171	0.48	0.60	0.50	154	6	5	1
10	20	13	0.61	0.67	0.58	5	2	5	-3
11	179	162	0.52	0.56	0.55	127	4	17	-13
12	202	209	0.49	0.51	0.51	160	3	6	-3
13	225	231	0.49	0.50	0.50	136	1	13	-12
14	51	25	0.67	0.87	0.63	110	27	6	21
15	195	83	0.70	0.58	0.54	159	5	1	4
16	4	142	0.03	0.53	0.51	30	4	16	-12
17	112	63	0.64	0.56	0.53	115	3	20	-17
18	166	203	0.45	0.54	0.53	103	6	10	-4
19	227	225	0.50	0.50	0.50	151	0	5	-5
20	0	28	0	0.61	0.54	39	46	7	39
21	219	215	0.50	0.51	0.52	116	3	11	-8
22	218	225	0.49	0.50	0.50	155	6	6	0
23	211	216	0.49	0.49	0.51	140	10	7	3
24	16	117	0.12	0.53	0.56	52	6	27	-21
<i>M</i>	138.96	138.92	0.481	0.57	0.53	117.67	8.38	9.71	-1.33
<i>SD</i>	81.69	77.21	0.22	0.08	0.03	46.65	11.30	6.32	13.88

PNT = Philadelphia Naming Test; P = phonological; S = semantic

Research Question 2: Primacy/Recency Bias and Word Retrieval Breakdown

Research question 2 explored the relationship between error location in word pair repetition and word retrieval error type. Reliability calculations (Cohen's kappa, Landis & Koch,

1977) on the PNT and word pair repetition responses demonstrated that these measures were highly reliable. A kappa coefficient of .840 (almost perfect agreement) was found for intra-rater naming error coding and of .958 (almost perfect agreement) for intra-rater word pair repetition coding. A coefficient of .795 (substantial agreement) was found for inter-rater naming error coding and of .919 (almost perfect agreement) for inter-rater word pair repetition coding.

Individual word retrieval type and primacy bias scores are listed in Table 3. In addition to the correlation of P-S score with primacy, P and S scores were correlated with primacy bias because these raw scores provide information about error frequency (Table 4). No significant correlation was found between P score and primacy, $r(22) = -.367$, $p = .078$, though a trend in the opposite of the predicted direction was observed. That is, as P score increased, primacy bias decreased. No significant correlation was found between S score and primacy or P-S score and primacy.

Table 4. *Pearson correlation table: Primacy bias and word retrieval impairment type*

<i>Outcome Measure</i>	<i>M</i>	<i>SD</i>	<i>n</i>	P score	S score	P-S score	Primacy
P Score	8.38	11.30	24	--	-.18	.89 **	-.37
S Score	9.71	6.32	24	-.18	--	-.60 **	-.17
P-S Score	-1.33	13.88	24	.89 **	-.60 **	--	-.22
Primacy Bias	0.48	0.22	24	-.37	-.17	-.22	--

n = number of participants P = phonological; S = semantic

** $p < .01$

Table 5. *Pearson correlations: Frequency, imageability, and word retrieval impairment type*

<i>Outcome Measure</i>	<i>M</i>	<i>SD</i>	<i>n</i>	P score	S score	P-S score	Freq.	Image.
1. P Score	8.38	11.30	24	--	-.18	.89 **	.41 *	.39
2. S Score	9.71	6.32	24	-.18	--	-.60 **	.02	-.25
3. P-S Score	-1.33	13.88	24	.89 **	-.60 **	--	.32	.43 *
4. Freq. Bias	0.53	0.03	24	.41 *	.02	.32	--	.82 **
5. Image. Bias	0.57	0.08	24	.39	-.25	.43 *	.82 **	--

Research Question 3: Imageability/Frequency Bias and Word Retrieval Breakdown

Research question 3 explored the relationship between frequency and imageability biases in a word pair repetition task and word retrieval error type. In addition to the correlation of P-S scores with frequency scores, P and S scores were correlated with frequency bias score (Table 5). A significant positive correlation was found between P score and frequency bias, $r(22) = .406$, $p = .049$ (medium correlation): as P score (raw # of phonological errors) increased, frequency bias increased. No other relationships of interest were significant. In addition to the correlation of P-S scores with imageability scores, P and S scores were correlated with imageability bias score (Table 5). Consistent with the predictions, a significant positive correlation was found between P-S score and imageability bias, $r(22) = .429$, $p = .036$ (medium correlation): As the number of phonologically related nonword errors relative to semantically related errors increased, imageability bias increased. No other relationships of interest were significant.

Discussion

The purpose of this study was to determine whether a linguistically specified STM system supports word retrieval. The findings are interpreted in the context of a temporary linguistic activation process that partly underlies both verbal STM and word retrieval.

Domain Specificity of STM in Word Retrieval

The large positive correlation between word pointing span length and PNT accuracy, along with non-significant associations between the Corsi Block Task and both 1) word pointing span and 2) PNT accuracy, demonstrated a domain-specific relationship between verbal STM and word retrieval. Because a relatively pure verbal STM task (i.e., word pointing span) was used, this result was not influenced by both tasks requiring a verbal output. These results warrant careful investigation of the nature of the STM mechanism that supports word retrieval.

Primacy Bias and Word Retrieval Impairment Type

The lack of a positive correlation between primacy bias and word retrieval impairment type differs from the significant positive association between primacy bias and receptive language impairment type shown by Martin and Saffran (1997). In interpreting this discrepancy, the difference in timing between the receptive tasks, during which auditory input must be processed quickly (e.g., hearing two words and making a rhyme judgment), and the word retrieval task used in the present study must be considered. As in verbal STM tasks, where an immediate response is required, performance on receptive language tasks likely requires rapid spread of linguistic activation. In the present study's naming task, where participants had 30 seconds to respond, linguistic timing is likely much more flexible. In the allotted response window, error detection mechanisms that slowed or re-initiated the activation stream could have been in play. There is a possibility, then, that both word retrieval and verbal STM tasks depend on the same linguistic spreading activation process, but they operate on different time courses. The intricately timed word pair repetition task likely required much more rapid linguistic activation, leading to subtle differences in the activation of the first word (more strongly supported by semantic activation) and the second word (more strongly supported by phonological activation). Conversely, the word retrieval (PNT) task did not require participants to respond quickly, so the activation speed of semantic, lexical, and phonological features necessary to correctly name each picture likely varied within and between participants. Thus, the insignificant correlation between primacy bias and word retrieval impairment type may be partially explained by timing differences between the verbal STM (word pair repetition) and word retrieval (PNT) tasks.

A related issue is the question of the time course over which primacy/recency effects

might be observed in individuals with aphasia. Though the present study derived primacy scores from word pair repetition, Martin and colleagues (2002) later demonstrated a notable association between primacy bias in a 4-word string repetition task and receptive language impairment, a finding that was contingent on participants' span size (individuals with spans of 3.5 or lower did not show this association). Individual differences in word pointing span length (ranging from 1-4.05, Mean = 2.46, SD = .096) may thus have contributed to the null results. Though most individuals demonstrated a serial position bias on the word pair repetition task, individuals with word pointing span length scores below 3 ($n = 15$, span length ranging from 1-2.2) tended to demonstrate larger serial position effects on the word pair repetition task than individuals with word pointing span length scores above 3 ($n = 9$, span length ranging from 3.2-4.05). Eleven of the 15 individuals with lower span length scores had a primacy bias greater than 5% above or below 50% (a score of 50% indicates no serial position bias), while only one of the nine individuals with higher span length scores demonstrated a serial position bias of more than 5%. Thus, though individuals with word pointing span length scores above 3 items may have demonstrated serial position effects in a verbal STM task involving the repetition of 3 or more words, the repetition of word pairs may have been too simple to elicit these effects.

Along with individual differences in word pointing span length, individual differences in the dependence on lexical-semantics during the word pair repetition task must be considered. Though extant work has demonstrated potent influences of lexical-semantic processing on repetition, the task can nevertheless be accomplished solely through phonological activation. Even if an individual demonstrates a marked impairment in phonological relative to semantic processing (i.e., high P-S score), he/she may still not be able to access semantics efficiently enough to compensate for the phonological impairment. In this case, the predicted positive

correlation between primacy bias and P-S score would not be expected. If individuals are relying mostly on phonological processing to complete the repetition task, the second word should be easier to repeat (recency bias) because its phonemes are activated closest to the time of recall, a prediction which is consistent with the observed trend towards a negative correlation between primacy bias and P score.

Though the issues discussed above could have affected the results, based on the findings as a whole, verbal STM and word retrieval, at least as measured in this study, do not appear to be supported by shared linguistic activation *timing*. Despite this conclusion, verbal STM and word retrieval may be subserved by shared linguistic nodes that differ in their activation timing depending on the task. The discussion turns to research question 3 to explore this possibility.

Imageability and Frequency Biases and Word Retrieval Impairment

While the observation of a primacy bias in word pair repetition likely depends on intricate activation *timing*, which creates differential activation patterns between the first and second word to be repeated, imageability and frequency biases likely arise due to a word's overall activation *strength*. According to the IA model, linguistic nodes rest at varying activation levels. Lexical nodes' resting levels depend on the number of previous encounters with their corresponding words (frequency), while semantic nodes' resting activation levels depend on the number of semantic features connected to a word (imageability) (Dell et al., 1997; Nickels & Howard, 1994). The higher a node's resting activation level, the longer it can be kept active and the more efficiently it can activate nodes at neighboring levels (Martin & Saffran, 1992, as cited by Nickels & Howard, 1994). The analysis of associations between frequency/imageability biases and word retrieval yielded mixed results. The positive significant correlation between imageability bias and P-S score is consistent with the study's predictions, while the insignificant

correlation between frequency bias and P-S score is not (though, notably, the significant positive correlation between frequency bias and P score *is* consistent with the predictions).

To interpret the lack of a positive correlation between frequency and P-S score, it is important to consider that, while word frequency has typically been thought to influence the first step of word retrieval (lexical selection; Dell et al., 1997), studies have demonstrated that individuals with aphasia make significantly fewer semantic *and* phonological errors on high frequency than low frequency words (Kittredge et al., 2008). This finding has been explained by a holistic influence of frequency on linguistic (i.e., both lexical and phonological) activation (Bastiaanse, Wieling, & Wolthuis, 2015), which may explain the modest associations between frequency and language impairment type found by Martin and Saffran (1997) and in the current study. The imageability manipulation, conversely, works specifically at the semantic level, reflecting a word's semantic richness (i.e., how many semantic features are associated with that word) (Martin & Saffran, 1992; Nickels & Howard, 1994). The significant positive correlation between P-S score and imageability bias suggests that verbal STM and word retrieval may share a common underlying process related to overall linguistic activation strength. Perhaps temporary activation of the same linguistic representations subserves both types of tasks. For example, individuals who make predominately semantic errors in naming and demonstrate no evidence of an imageability bias on word span tasks might do so in part due to diminished semantic activation strength. Taken together with results of research questions 1 and 2, the findings reveal that the STM system that supports word retrieval is, at least in large part, language specific, and that it is likely the overall strength of linguistic activation rather than the timing of activation transmission that governs this link. The results are inconsistent with models that view the temporary retention of verbal information as an isolated process completely separate from

language processing, and supportive of a partial dependence of word retrieval and verbal short-term memory on a shared temporary interactive linguistic activation process.

In addition to the aforementioned interpretations, the lack of significant correlations between S score and imageability/frequency biases deserves mention. One methodological factor is that in naming tasks, semantic activation is boosted by the picture, which may cause the raw number of semantic errors to be lower than if the word was produced in conversation. Another possible confound involves visual confusions during naming. For example, some participants called the picture whose target was *bowl* a *cup* (a possible visual confusion due to the somewhat ambiguous picture representing the word *bowl*), an error that would be coded as semantic in accordance with PNT rules. The raw number of semantic errors could thus have been overestimated, a difficult issue to avoid even in thoroughly normed naming tests.

General Discussion

The results as a whole suggest that word production, as measured by picture naming, is more dependent on overall representational strength than on intricate spreading activation timing. The same linguistic representations may support both word retrieval and word pair repetition, but perhaps the spread of linguistic activation follows different time courses in these two tasks.

Clinical Implications. The analysis of speech errors can reveal important insights about the linguistic level(s) at which a linguistic impairment lies; however, it is also a time-consuming and elusive process. The results suggest that imageability bias on verbal STM tasks may be a window into an individual's word retrieval impairment type (i.e., the greater the imageability bias, the more phonological the impairment, relative to semantic). While replication and extension of this work is necessary in order to determine whether imageability bias can accurately predict word retrieval impairment type, the possibility of a more efficient way to get

at the nature of an individual's word retrieval impairment is a compelling one.

Limitations and Future Directions. Several theoretical and methodological issues deserve mention, the first of which is the limitation of using a repetition-based task to measure verbal STM. The interactive activation model of verbal STM focuses on the pattern of temporary linguistic activation during the intermediate step between hearing a word pair and producing it; however, the model does not account for the complex interactions between this moment of relatively pure temporary storage and the input and output demands of this task (i.e., auditory comprehension and spoken production). While it may be possible to make the word pair task purer with the use of a picture pointing response, this would be very challenging given the open set of words used and the low imageability of some words. Nevertheless, the limitations of using a repetition task to test verbal STM should always be considered. On the other hand, the use of a word pointing span as the measure of verbal STM can be argued to be problematic as well. Because participants must match word sequences to pictures, such a task can be argued to require a considerable amount of attentional resources, and thus may not be a pure verbal STM measure. Including both pointing and repetition spans in future studies may compensate for the shortcomings of each task and provide a more complete picture of verbal STM capacity.

Additionally, several modifications to the word retrieval and word pair repetition tasks should be considered. Two changes could be made to make the word retrieval task more in-line with the rapid activation timing requirements of word retrieval in natural settings: 1) limiting the amount of time the picture is present on the screen and 2) limiting the allotted response time. Allowing the picture to be present only for a brief period of time (Martin, 2012) would require more active generation of features at the conceptual-semantic processing level, while limiting the response time would better approximate the rapid spread of activation required to produce a

word in conversation. Furthermore, a re-analysis of existing data to determine how many word pair repetition trials must be administered in order to estimate imageability and frequency biases may maximize the clinical applicability of this work. While the current 240-trial task is not clinically feasible, a re-analysis may show that fewer trials yield similar imageability and frequency bias scores, thus increasing the task's potential diagnostic utility. Additionally, looking at imageability and serial position biases in verbal STM tasks requiring the repetition of three or more words as they relate to word retrieval impairment type might reveal further insights, particularly in individuals with relatively high word span length scores.

Last but not least, though this study was not an investigation of the extent to which language production and comprehension rely on a shared verbal STM process, comparisons of the current results with that of Martin and Saffran (1997) provide a window into the possible partial reliance of the two domains on the same temporary interactive linguistic activation process. In the future, administration of word retrieval, comprehension, and verbal STM measures to the same group of participants would elucidate the extent to which these linguistic domains share a common temporary storage (i.e., verbal STM) process. This investigation would be clinically significant, in that identifying processes that are shared by language production and comprehension tasks and understanding their breakdown can help hone in on what to treat to maximize treatment generalization across language domains.

Conclusion

The present study demonstrated notable associations between word retrieval impairment type (i.e., relatively more semantic or phonological) and word pair repetition (i.e., a measure of verbal STM), which at least partly supported a linguistically-specified STM system underlying the retrieval of words. The results are problematic for models that view STM as a domain

separate from language, and supportive of the interactive activation model of STM at the heart of this study. Perhaps it is time to rethink the classic distinction between language and STM, to investigate further the idea that access to linguistic representations in word retrieval is dependent on a linguistically-specified temporary activation process, and to let go of the idea that a STM system exists that is wholly separable from the process it supports. The continued investigation of clinically-driven processes (e.g, STM and attention) that aid access to language representations has the potential to inform and influence clinical practice, eventually leading to the creation of impairment-driven and generalizable treatments for aphasia.

Acknowledgements

This study was conducted at the University of Washington Aphasia Research Laboratory. We would like to thank all of the participants and their families for their time and effort. The first author was supported by an NIDCD Institutional Training Grant under grant number T32000033 during the completion of this research. Research reported in this publication was also supported by the NIDCD of the National Institutes of Health under award number R01DC013196 (PI: Nadine Martin). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

References

- Albert, M. L. (1976). Short-term memory and aphasia. *Brain and Language*, 3, 28-33. doi: 10.1016/0093-934X(76)90003-1
- Allen, R., & Hulme, C. (2006). Speech and language processing mechanisms in verbal serial recall. *Journal of Memory and Language*, 55, 64-88. doi:10.1016/j.jml.2006.02.002
- Baddeley, A., & Hitch, G. J. (1974). Working Memory. In G. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8, pp. 47-90). San Diego: Academic Press.

- Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences*, 4, 417-423. doi: 10.1016/S1364-6613(00)01538-2
- Ballard, K. J., Granier, J. P., & Robin, D. A. (2000). Understanding the nature of apraxia of speech: Theory, analysis, and treatment. *Aphasiology*, 14, 969-995. doi: 10.1080/02687030050156575
- Bastiaanse, R., Wieling, M., & Wolthuis, N. (2015). The role of frequency in the retrieval of nouns and verbs in aphasia. *Aphasiology*. doi: 10.1080/02687038.2015.1100709
- Bourassa, D. C., & Besner, D. (1994). Beyond the articulatory loop: A semantic contribution to serial order recall of subspan lists. *Psychonomic Bulletin & Review*, 1, 122-125. doi: 10.3758/BF03200768
- Brener, R. (1940). An experimental investigation of memory span. *Journal of Experimental Psychology*, 26, 467-482. doi: 10.1037/H0061096
- Brysbaert, M., & New, B. (2009). Moving beyond Kucera and Francis: a critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavioral Research Methods*, 41, 977-990. doi: 10.3758/BRM.41.4.977
- Cahana-Amitay, D., & Albert, M. L. (2015). Neuroscience of aphasia recovery: the concept of neural multifunctionality. *Current Neurology and Neuroscience Reports*, 15, doi: 10.1007/s11910-015-0568-7
- Chang, D. F. (1995). Ophthalmic examination. In D. Vaughan, T. Asbury & P. Riordan-Eva (Eds.), *General Ophthalmology*. Norwalk: Appleton & Lange.

- Coltheart, M. (1981). The Mrc Psycholinguistic Database. *Quarterly Journal of Experimental Psychology Section a-Human Experimental Psychology*, *33*(Nov), 497-505. doi: 10.1080/14640748108400805
- Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin*, *104*, 163-191. doi: 10.1037/0033-2909.104.2.163
- De Renzi, E., & Nichelli, P. (1975). Verbal and non-verbal short-term memory impairment following hemispheric damage. *Cortex*, *11*, 341-354. doi: 10.1016/S0010-9452(75)80026-8
- Dell, G. S., Schwartz, M. F., Martin, N., Saffran, E. M., & Gagnon, D. A. (1997). Lexical access in aphasic and nonaphasic speakers. *Psychological Review*, *104*, 801-838. doi: 10.1037//0033-295X.104.4.801
- Goldrick, M. & Rapp, B. (2007). Lexical and post-lexical phonological representations in spoken production. *Cognition*, *102*, 219-260. doi: 10.1016/j.cognition.2005.12.010
- Hulme, C., Maughan, S., & Brown, G. D. A. (1991). Memory for familiar and unfamiliar words: Evidence for a long-term memory contribution to short-term memory span. *Journal of Memory and Language*, *30*, 685-701. doi: 10.1016/0749-596X(91)90032-F
- Itoh, M., Sasanuma, S., & Ushijima, T. (1979). Velar movements during speech in a patient with apraxia of speech. *Brain and Language*, *7*, 227-239. doi: 10.1016/0093-934X(79)90019-1
- Kasselimis, D. S., Simos, P. G., Economou, A., Peppas, C., Evdokimidis, I., & Potagas, C. (2013). Are memory deficits dependent on the presence of aphasia in left brain damaged patients? *Neuropsychologia*, *51*, 1773-1776. doi: 10.1016/j.neuropsychologia.2013.06.003

- Landis, J. R., & Koch, G. G. (1977). The Measurement of observer agreement for categorical data. *Biometrics*, *33*, 159-174. doi: 10.2307/2529310
- Lang, C. J. G., & Quitz, A. (2012). Verbal and nonverbal memory impairment in aphasia. *Journal of Neurology*, *259*, 1655-1661. doi:10.1007/s00415-011-6394-1
- Laures-Gore, J., Marshall, R. S., & Verner, E. (2011). Performance of individuals with left hemisphere stroke and aphasia and individuals with right brain damage on forward and backward digit span tasks. *Aphasiology*, *25*, 43-56. doi: 10.1080/02687031003714426
- Lauro, L. J. R., Reis, J., Cohen, L. G., Cecchetto, C., & Papagno, C. (2010). A case for the involvement of phonological loop in sentence comprehension. *Neuropsychologia*, *48*, 4003-4011. doi: 10.1016/j.neuropsychologia.2010.10.019
- Madigan, S. (1980). The serial position curve in immediate serial-recall. *Bulletin of the Psychonomic Society*, *15*, 335-338. doi: 10.3758/BF03334550
- Martin, N. (2012). Managing communication deficits associated with memory disorders. In R. Peach & L. Shapiro (Eds.), *Cognition and Acquired Language Disorders: A Process-Oriented Approach* (pp. 275-297). St. Louis: Mosby.
- Martin, N., & Ayala, J. (2004). Measurements of auditory-verbal STM span in aphasia: Effects of item, task, and lexical impairment. *Brain and Language*, *89*, 464-483. doi: 10.1016/j.bandl.2003.12.004
- Martin, N., Ayala, J., & Saffran, E. M. (2002). Lexical influences on serial position effects in verbal STM span in aphasia. *Brain and Language*, *83*, 92-95.
- Martin, N., & Gupta, P. (2004). Exploring the relationship between word processing and verbal short-term memory: Evidence from associations and dissociations. *Cognitive Neuropsychology*, *21*, 213-228. doi:10.1080/02643290342000447

- Martin, N., & Saffran, E. M. (1992). A computational account of deep dysphasia: evidence from a single case study. *Brain and Language, 43*, 240-274. doi: 10.1016/0093-934X(92)90130-7
- Martin, N., & Saffran, E. M. (1997). Language and auditory-verbal short-term memory impairments: Evidence for common underlying processes. *Cognitive Neuropsychology, 14*, 641-682. doi: 10.1080/026432997381402
- Martín-Loeches, M., Hinojosa, J. A., Fernández-Frías, C., & Rubia, F. J. (2001). Functional differences in the semantic processing of concrete and abstract words. *Neuropsychologia, 39*, 1086-1096. doi: 10.1016/S0028-3932(01)00033-1
- Mathy, F., & Feldman, J. (2012). What's magic about magic numbers? Chunking and data compression in short-term memory. *Cognition, 122*, 346-362. doi: 10.1016/j.cognition.2011.11.003
- Mauszycki, S. C., Dromey, C., & Wambaugh, J. L. (2007). Variability in apraxia of speech: A perceptual, acoustic, and kinematic analysis of stop consonants. *Journal of Medical Speech-Language Pathology, 15*, 223-242. doi: 10.1080/02687030903438516
- McNeil, M. R., Odell, K., & Tseng, C. H. (1991). Toward the integration of resource allocation into a general theory of aphasia. *Clinical Aphasiology, 20*, 21-39.
- Miller, G. A. (1956). The magical number seven plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 63*, 81-97. doi: 10.1037/h0043158
- National Institute of Neurological Disorders and Stroke (2015, September 11). Aphasia Information Page. Retrieved from <http://www.ninds.nih.gov/disorders/aphasia>

- Nickels, L., & Howard, D. (1994). A frequent occurrence? Factors affecting the production of semantic errors in aphasic naming. *Cognitive Neuropsychology, 11*, 289-320. doi: 10.1080/02643299408251977
- Nickels, L., & Howard, D. (1995). Phonological errors in aphasic naming: Comprehension, monitoring and lexicality. *Cortex, 31*, 209-237. doi: 10.1016/S0010-9452(13)80360-7
- Odell, K., McNeil, M. R., Rosenbek, J. C., & Hunter, L. (1990). Perceptual characteristics of consonant production by apraxic speakers. *Journal of Speech and Hearing Disorders, 55*, 345-359. doi: 10.1044/jshd.5502.345
- Potagas, C., Kasselimis, D., & Evdokimidis, I. (2011). Short-term and working memory impairments in aphasia. *Neuropsychologia, 49*, 2874-2878. doi:10.1016/j.neuropsychologia.2011.06.013
- Raven, J., Raven, J. C., & Court, J. H. (1998). *Manual for Raven's progressive matrices and vocabulary scales*. Oxford: Oxford Psychologists.
- Roach, A., Schwartz, M. F., Martin, N., Grewal, R. S., & Brecher, A. (1996). The Philadelphia Naming Test: Scoring and rationale. *Clinical Aphasiology, 24*, 121-133.
- Roodenrys, S., Hulme, C., Lethbridge, A., Hinton, M., & Nimmo, L. M. (2002). Word-frequency and phonological-neighborhood effects on verbal short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*, 1019-1034. doi: 10.1037/0278-7393.28.6.1019
- Rosenbek, J. C., LaPointe, L. L., & Wertz, R. T. (1989). Nosology: What aphasia is and what it is not. *Aphasia: A clinical approach* (pp. 34-54). Austin: PRO-ED.

- Schilling, H. E. H. (1998). Comparing naming, lexical decision, and eye fixation times: Word frequency effects and individual differences. *Memory & Cognition*, *26*, 1270-1281. doi: 10.3758/BF03201199
- Schuchardt, K., Maehler, C., & Hasselhorn, M. (2011). Functional deficits in phonological working memory in children with intellectual disabilities. *Research in Developmental Disabilities*, *32*, 1934-1940. doi: 10.1016/j.ridd.2011.03.022
- Shelton, J. R., Martin, R. C., & Yaffee, L. S. (1992). Investigating a verbal short-term memory deficit and its consequences for language processing. In D. I. Magnolin (Ed.), *Cognitive neuropsychology in clinical practice* (pp. 131-167). New York: Oxford University Press.
- Swinburn, K., Porter, G., & Howard, D. (2004). *Comprehensive Aphasia Test*. New York: Psychology Press.
- Unsworth, N., & Engle, R. W. (2007). On the division of short-term and working memory: an examination of simple and complex span and their relation to higher order abilities. *Psychological Bulletin*, *133*, 1038-1066. doi: 10.1037/0033-2909.133.6.1038
- Vaden, K. I., Halpin, H. R., & Hickok, G. S. (2009). Irvine Phonotactic Online Dictionary, Version 1.4 [Data File] Available from <http://www.iphod.com>
- Wilshire, C. E., Keall, L. M., & O'Donnell, D. J. (2010). Semantic contributions to immediate serial recall: Evidence from two contrasting aphasic individuals. *Neurocase*, *16*, 331-351. doi: 10.1080/13554791003620256
- Wright, H. H., & Fergadiotis, G. (2012). Conceptualising and measuring working memory and its relationship to aphasia. *Aphasiology*, *26*, 258-278. doi: 10.1080/02687038.2011.604304