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The Time Course of Priming in Aphasia

An Exploration of Learning Along a Continuum of Linguistic Processing Demands

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This study investigates learning in aphasia as manifested through automatic priming effects. There is growing evidence that people with aphasia have impairments beyond language processing that could affect their response to treatment. Therefore, better understanding these mechanisms would be beneficial for improving methods of rehabilitation. This study assesses semantic and repetition priming effects at varied interstimulus intervals, using stimuli that are both nonlinguistic and linguistic in tasks that range from requiring nearly no linguistic processing to requiring both lexical and semantic processing. Results indicate that people with aphasia maintain typical patterns of learning across both linguistic and nonlinguistic tasks as long as the implicit prime-target relationship does not depend on deep levels of linguistic processing. As linguistic processing demands increase, those with agrammatic aphasia may require more time to take advantage of learning through implicit prime-target relationships, and people with both agrammatic and nonagrammatic aphasia are more susceptible to breakdown of the semantic networks as processing demands on that system increase. **Key words:** *aphasia*, *automatic spreading activation*, *delayed activation hypothesis*, *priming*

ONE form of learning that has been investigated in aphasia is the mechanism of *priming*. Priming occurs when a person's response to a stimulus (a *target*) is influenced by his or her exposure to another stimulus (a *prime*); for example, a person is likely to be faster to recognize that a target of *nurse* is a real word when he or she has previously seen the prime word *doctor*. Priming is a form of learning at its most basic level, as the cognitive–linguistic system uses information from a prime to influence its response to a subsequent target. Priming is thought to be mediated by spreading activation, the fundamental mechanism of energy propagation that is responsible for activity within linguistic networks (Balota & Lorch, 1986; Collins & Loftus, 1975; Neely, 1977, 1991). This process occurs automatically, without conscious awareness, reflection, or control.

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There is some evidence that people with aphasia (PWA) have alterations in the timing of spreading activation within linguistic networks, which would influence their ability to learn through priming. Prior research has demonstrated that priming effects may be delayed for PWA (Silkes & Rogers, 2012) and particularly for people with anterior lesions and agrammatism (Love, Swinney, Walenski, & Zurif, 2008; Prather, Zurif, Love, & Brownell, 1997). In the context of functional communication, impaired timing of spreading activation can impair the timely retrieval of words and construction of sentences (Dell, 1986; Dell, Schwartz, Martin, Saffran, & Gagnon, 1997), as well as the ability to interpret incoming information for comprehension (Mätzig, Vasishth, Engelmann, Caplan, & Burchert, 2018). In the context of language rehabilitation, changes in spreading activation can impair the ability to make use of cues and integrate information, impeding learning in the therapeutic context.

Although there is convincing evidence that PWA may have altered timing of activation within the language network, it is still unclear how much of this problem is language-specific and how much may be domain-general (i.e., shared across cognitive-processing domains other than language). There is existing evidence that PWA are impaired in areas that have not traditionally been considered linguistic, such as attention and working memory (Caspari, Parkinson, LaPointe, & Katz, 1998; Murray, Holland, & Beeson, 1997; Robinson, Shallice, & Cipolotti, 2005; Schnur, Schwartz, Brecher, & Hodgson, 2006; Wright & Shisler, 2005), but the precise nature of which mechanisms may be affected has not yet been clearly defined. If impaired spreading activation is part of the problem in the attention and working memory systems, which are critical for both implicit and explicit learning in aphasia therapy, it would have implications for aphasia treatment methods. In addition, if PWA were to be found to have delayed automatic spreading activation in minimally or nonlinguistic tasks, this would further support the growing evidence that aphasia involves impairments that extend beyond "core" language domains such as lexical-semantics.

Achieving a better understanding of the status of automatic spreading activation across a range of linguistic processing demands could either point toward a need to develop treatment methods that directly address fundamental (i.e., not necessarily linguistic) processes or point toward developing methods that bootstrap relatively intact fundamental skills to make aphasia therapy more efficient and effective. Therefore, this study was undertaken to explore the specific mechanism of automatic spreading activation across tasks that involve varying degrees of linguistic processing, from full lexical-semantic processing to minimal- (or non-) linguistic processing (see Figure 1). Specifically, this study investigated the time course of priming effects for PWA across a range of tasks and whether the time course differs from that obtained from age-matched neurotypical control (AMC) participants. Priming was manipulated to require either a shallow level of spreading activation (i.e., form repetition priming) or a deeper level of spreading activation through a semantic network. The implicit priming task manipulation occurred in the context of a range of explicit tasks that engaged varying levels of linguistic processing, based on prior work that suggests that the nature of how linguistic networks are engaged will vary depending on the processing tasks required (e.g., Love, Haist, Nicol, & Swinney, 2006). We predicted that at least some PWA would show semantic priming effects at later intervals than AMC participants, with greater impairment in the context of the more demanding Semantic Decision task than in the Lexical Decision task. In addition, we predicted that PWA might show altered patterns of repetition priming, as well, across stimulus types; this would reflect impairment of the basic mechanism of automatic spreading activation across cognitive domains.

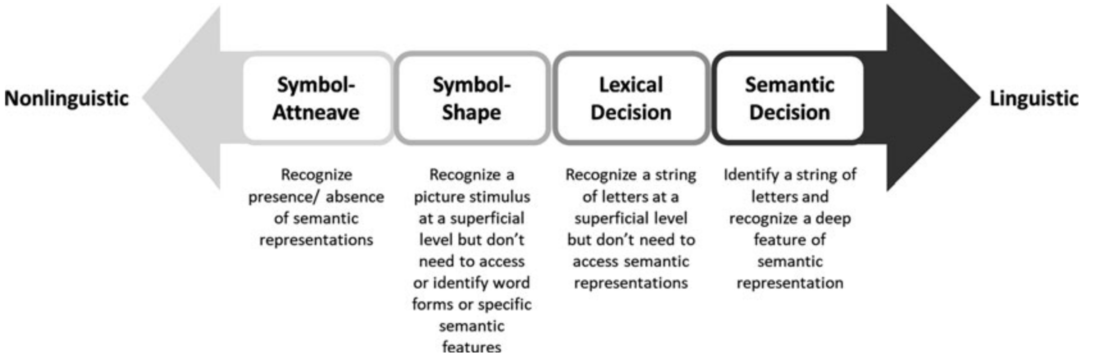

Figure 1. Continuum of linguistic engagement required for each task.

METHODS

All methods were approved by both the University of California San Diego and the San Diego State University Institutional Review Boards.

Participants

Two groups participated in this within-subjects study: 13 PWA and 7 AMC participants. Participants with aphasia were recruited from an existing participant database at San Diego State University and from the SDSU Speech-Language Clinic. The AMC participants were recruited from the San Diego community, through an existing participant database and advertisements posted in the SDSU Speech-Language Clinic. A summary of demographic information for all participants is provided in Tables 1 and 2.

The mean age of PWA at the time of testing was 50.1 years (range: 32–71 years). Of the 13 participants, nine had nonfluent, agrammatic aphasia (hereafter, the *agrammatic* group) as per clinical consensus and performance on standardized language assessments (see later), whereas four were fluent and nonagrammatic (hereafter, the *nonagrammatic* group). All PWA had experienced a single, unilateral left-hemisphere stroke, were native English speakers, had normal or corrected-to-normal visual and auditory acuity, as measured by vision and hearing screenings at the start of the experimental protocol, and were right-handed before their stroke. The clinical diagnosis of aphasia was made on the basis of the administration of standardized language testing to determine the extent and severity of each participant's language impairment in the areas of fluency and auditory comprehension ability. Testing for this purpose included the Western Aphasia Battery—Revised (WAB-R; Kertesz, 2006) and the Boston Naming Test (Kaplan, Goodglass, & Weintraub, 2001). All participants had intact single word reading, as determined by the picture–word matching subtest of the WAB-R, and intact basic semantic processing as determined by a picture-based semantic category membership decision task. The designation of being agrammatic or nonagrammatic was made on the basis of clinical consensus along with a fluency rating score lower than 6 on the WAB-R picture description task and/or below-chance performance on comprehension of noncanonical (object-relative) sentences on the Subject-relative Object-relative Active and Passive (SOAP) Test of Auditory Sentence Comprehension (Love & Oster, 2002). All PWA were physically and neurologically stable (i.e., at least 6 months postonset), with no reported history of active or significant alcohol and/or drug abuse, active psychiatric illness or intellectual disability, and/or other significant brain disorder or dysfunction.

The mean age for the AMC participants was 58 years (range: 51–67 years; not significantly different from the PWA, $t(18) = -1.626$, $p = .121$). All of the AMC participants were monolingual native English speakers with normal or

Table 1. Demographic information for participants with aphasia and the tasks for which they provided complete data[a]

	Participant	Task Inclusion	Sex	Years Post-stroke	Education (Years)	Age (Years)	WAB AQ (/100)	BNT (/60)	SOAP Object-Relative	WAB Written Word–Picture Matching	Semantic Category Membership Recognition Task
Agrammatic PWA	LHD019	LD, SD, SS, SA	F	16	12	61	54.1	19	20%	100%	100%
	LHD040	LD, SS, SA	M	5	16	71	76.7	42	50%	100%	94%
	LHD101	LD, SD, SA	M	4	20	62	82.4	54	30%	98%	100%
	LHD130	LD, SD, SS, SA	M	3	16	58	81.1	17	60%	100%	100%
	LHD138	LD, SD, SS, SA	M	12	14	33	70.1	21	20%	100%	100%
	LHD139	LD, SD, SS, SA	M	12	14	32	71.6	52	60%	100%	100%
	LHD140	SD, SA	F	10	16	37	75.7	44	50%	100%	94%
	LHD142	LD, SS	M	1	8	55	80.6	45	40%	100%	94%
	LHD145	LD, SS	M	8	16	55	38.4	5	40%	100%	87%
Nonagrammatic PWA	LHD009	LD, SD, SS, SA	M	10	17	50	76.3	51	55%	100%	100%
	LHD132[b]	LD, SS	M	6	16	47	N/A	56	75%	100%[b]	94%
	LHD146[c]	LD, SD, SS, SA	F	1	16	40	95.4	54	95%	100%	100%
	LHD148[b]	LD, SS	M	7 mo.	14	51	N/A	52	90%	100%[b]	-

Note. BNT = Boston Naming Test; BNT severity levels: ≤20 = severe, 20–40 = moderate, ≥40 = mild; LD = Lexical Decision Task; SA = Symbol/Attneave Decision Task; SD = Semantic Decision Task; SOAP = Subject-relative-Object-relative-Active-Passive Test of Sentence Comprehension (50% = chance performance); SS = Symbol/Shape Decision Task; WAB AQ = Western Aphasia Battery Aphasia Quotient; BDAE. WAB AQ severity levels: 0–25 = very severe; 26–50 = severe; 51–75 = moderate; ≥76 = mild.

[a]Participants with aphasia are separated here by their status as "agrammatic" versus "non-agrammatic" for ease of interpretation of post-hoc analyses.

[b]Participants LHD132 and LHD148 were given version 3 of the Boston Diagnostic Aphasia Exam, rather than the WAB. LHD132 achieved a severity score = 4 (mild); LHD148 achieved a severity score = 5 (mild).

[c]Participant LHD146 had mild aphasia with frequent circumlocution and language organization impairments, despite her high scores on standardized tests.

Table 2. Demographic information for age-matched typical control participants and the tasks for which they provided complete data.

	Participant	Task Inclusion	Sex	Education (Years)	Age (Years)	WRIT IQ	SOAP Object-Relative
Age-matched controls (AMC)	AMC081	LD, SD, SS	F	62	16	104	100%
	AMC109	LD, SD, SS	M	57	14	122	100%
	AMC121	LD, SD, SS, SA	M	67	14	94	100%
	AMC126	LD, SD, SS, SA	F	56	19	134	100%
	AMC131	LD, SD, SS, SA	F	51	14	109	100%
	AMC150	LD, SS	F	52	16	108	100%
	AMC152	LD, SD, SA	F	61	16	105	95%

Note. LD = Lexical Decision Task; SA = Symbol/Attneave Decision Task; SD = Semantic Decision Task; SOAP = Subject-Object-Active-Passive Test of Sentence Comprehension; SS = Symbol/Shape Decision Task; WRIT = Wide Range Intelligence Test.

corrected-to-normal visual and auditory acuity. They all scored within normal limits on the Wide Range Intelligence Test (Glutting, Adams, & Shelsow, 2000) and had no history of active or significant alcohol and/or drug abuse, active psychiatric illness or intellectual disability, and/or other significant brain disorder or dysfunction, as per participant self-report.

All participants, in both groups, received $15 for each testing session.

Experimental approach and design

To best capture automatic priming, we employed a computer-based list priming paradigm (Prather et al., 1997), which is designed to restrict priming to automatic effects. In the list priming paradigm, visual stimuli are presented sequentially and continuously (i.e., without breaks in the sequence of words being presented). Embedded within the continuous lists are experimental pairs (see details later), but these "pairs" are not distinguishable due to the continuous stimulus presentation format of the list priming paradigm task. Critically, this presentation format discourages participants from perceiving the stimuli as paired so that they cannot use explicit strategies to complete the task, which could obscure measurement of the implicit, unconscious process of automatic spreading activation (Prather & Swinney, 1988; Prather et al., 1997; Shelton & Martin, 1992). To capture the time course of automatic spreading activation, we manipulated the time between the offset of each stimulus and the onset of the next (the *interstimulus interval*; ISI).

This study involved a 3 × 2 × 4 repeated-measures design. Priming effects were measured for each participant at three different ISIs (500 ms, 1,000 ms, and 1,500 ms) with two different relatedness conditions (related primes and unrelated primes) across four different tasks that required different degrees and types of linguistic processing (see Figure 2 for an illustration of the various tasks and the decisions that participants made in each). Each testing day involved a single task at a single ISI. Under ideal circumstances, all

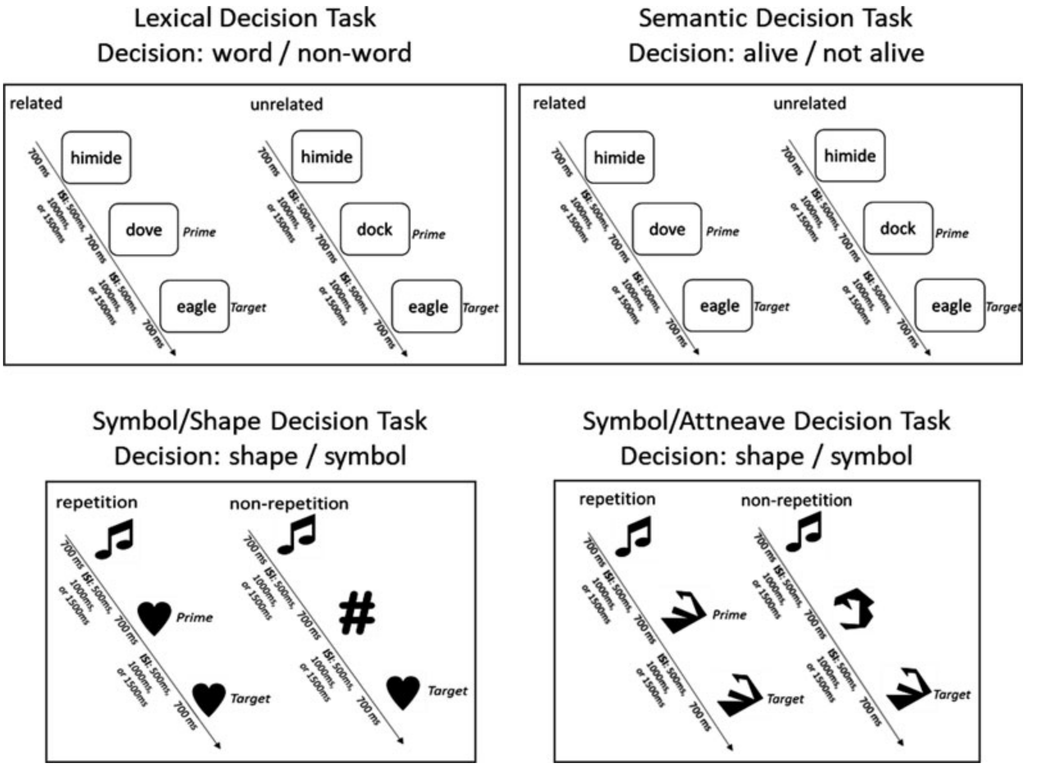

Figure 2. Examples of the task design (including stimulus timing) for the four tasks: (1) Lexical decision; (2) Semantic Decision; (3) Symbol/Shape Decision; and (4) Symbol/Attneave Decision, along with the binary decision that was made for each task. For all tasks, the comparison of interest was the reaction time to the target in the related/repetition condition as compared with the unrelated/nonrepetition condition.

participants engaged in all tasks and conditions. The sequence of task presentation was balanced across participants by way of a 3 × 3 Latin square rotation.

Experimental tasks

Lexical decision task

We begin by describing the Lexical Decision task because it is the most commonly used task in psycholinguistic research and, therefore, served as the basis for all other task manipulations. This task involved participants seeing strings of letters, with each string presented one at a time within a continuous presentation of stimuli, as described previously, and using button press responses on a two-button response box to indicate whether each string was a real word or not (full description of the stimuli for all tasks is provided later). The task was designed to require lexical processing of stimuli but not necessarily semantic processing, as the stimuli needed to be recognized as lexical items (words) or not (nonwords), but did not need to be semantically encoded to complete the task.

In addition to the semantic priming items embedded in the Lexical Decision task, a repetition priming condition was included. This condition was included to provide an equivalent condition for linguistic items as what was tested with nonorthographic items in the Symbol/Shape and Symbol/Attneave tasks described below, in which semantic priming was not possible (further explanation provided later). The repetition priming condition also provided a way to establish whether PWA demonstrate priming at a basic level that does not require a semantic relationship for priming to occur.

Semantic decision task

This task was designed to require both lexical processing (orthographic stimuli need to be recognized) and semantic processing (semantic features need to be accessed to allow comprehension) to provide a binary response of whether each stimulus presented was *alive* or *not alive*.

Symbol/identifiable shape decision

This task involved participants seeing black and white stimuli (described later) and using button press responses to indicate whether each item was a shape or a symbol. This task was designed to require minimal lexical or semantic processing, as participants could make this decision without accessing lexical forms (i.e., they did not need to know the name of the symbol or shape) and without accessing full semantic representation (i.e., they could make the judgment about whether each stimulus has extrinsic meaning through a shallow analysis without identifying those meanings).

Symbol/nonidentifiable shape (Attneave) decision

This task was identical to the Symbol/Shape task with the exception that, instead of identifiable shapes, the contrast condition was shapes that are nonlinguistic (see details later). As in the Symbol/Shape decision task, participants were asked to make a "symbol" or "shape" binary decision via button press response. This task was designed to minimize linguistic processing. In particular, the Attneaves have neither lexical nor semantic representation, so they cannot recruit lexical or deep semantic processing, although they may be assigned a value of "shape" in the process of performing the task; this is in stark contrast with the Semantic Decision, Lexical Decision, and Symbol/Shape tasks. For both Attneaves and Symbols, the task could be completed by simply recognizing whether the stimulus has meaning or not, without accessing that specific meaning for the Symbols.

Stimuli

The Lexical Decision and Semantic Decision tasks used orthographic stimuli whereas the Symbol/Shape and Symbol/Attneave tasks used minimally to nonlinguistic stimuli. Each of these is described later and stimuli for all tasks are available upon request.

Stimuli for the Lexical Decision and Semantic Decision tasks

These tasks involved strings of letters that were either real words or nonwords presented in 24-point Arial font. Two experimental lists of 378 items each were created for each of the three ISIs for a total of six lists altogether. Each list comprised semantically controlled pairs (a prime and a target, as described previously, including items that were preceded by an unrelated prime), repetition prime pairs (a prime and a target, as described previously, including items that were preceded by a nonidentical prime), and filler nonwords. In addition, there were target words that were not preceded by semantically related or identical primes.

The targets presented in the Lexical Decision task all reflected concrete, picturable nouns that were either animals (e.g., puppy) or human occupations (e.g., surgeon, wrestler, carpenter). Experimental lists were designed so that some of the real-word letter strings (which served as targets) were immediately preceded by words that were semantically related (which served as related primes). In addition, real-word strings that preceded targets but were semantically unrelated to them served as unrelated primes. There were 60 related word pairs, in which the related prime was a category coordinate of the target word (e.g., *dove*-eagle), and 60 matched control pairs with unrelated primes. The unrelated prime words were created by replacing the prime word from the related word pair with a word of the same length and word frequency (Francis & Kucera, 1982) that shared the initial letter as the related prime but was unrelated in meaning to the target word (e.g., *dock*-eagle).

Determination of semantically associated word pairs and unrelated pairs

Target words were selected from among those validated and used in a previous list priming paradigm with PWA (Prather et al., 1997). One hundred ninety-three target words were chosen and matched with one or two potential semantically related (category coordinate) words and potential unrelated words using the criteria stated previously. Semantically related words were initially selected on the basis of published norms (Jenkins, 1970; Keppel & Strand, 1970; Postman, 1970). Once semantically related words were identified, those pairs and the unrelated pairs were submitted to an association pretest. This association pretest was performed with 54 undergraduate students from the University of California San Diego who participated for course credit. The task was to use a 5-point Likert scale to rate how related the pairs were (1 = "not related at all," 5 = "very related"). Pairs were included in this study if the average rating for related items was more than 3.75 and for unrelated items was less than 2.75. Based on these results, 120 word pairs were chosen to be included in the task (60 related/60 unrelated), with 28 being animal pairs and 32 being human occupations. The average rating for related pairs was 4.45 (SD = 0.09) and for unrelated pairs was 1.76 (SD = 0.2); these were statistically different from one another ($t[118] = 38.81, p < .01$).

In addition to the semantically controlled prime-target pairs as described previously, the experimental lists for the Lexical Decision task also included 18 prime-target pairs that used repetition primes, that is, for these pairs within the Lexical Decision lists, the prime word and target word were the same (e.g., *clam* immediately followed by *clam*). Repetition priming word pairs were structured in the same manner as described for the semantically controlled pairs, with one list per ISI condition containing the repetition target preceded by its identical prime (the *repetition* condition) and the other list presenting the same target preceded by a wholly unrelated real word (the *nonrepetition* condition; see Figure 3).

The Lexical Decision task lists also included 174 phonologically pronounceable nonword filler items to make the presence of related words unpredictable. The nonword items were created by taking real words such as "moral" or "before" and changing one letter at either the beginning or the end of the word to create a nonword, such as "moraf" or "jefore."

The Semantic Decision task used the same experimental stimuli as the Lexical Decision task, with one exception: rather than using nonword filler items, those items were changed to inanimate nouns (requiring a *not alive* response) that included food items (e.g., pizza) and highly imageable objects (e.g.,

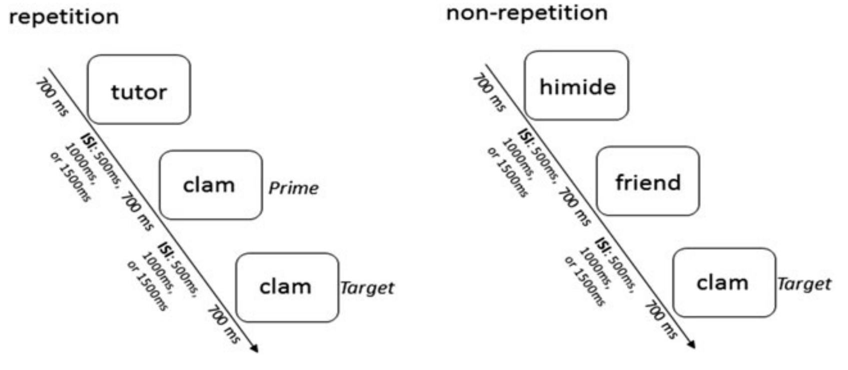

Figure 3. Example of the design (including stimulus timing) for the repetition priming conditions in the Lexical Decision and Semantic Decision tasks. For these tasks, the comparison of interest was the target in the repetition condition as compared with the target in the nonrepetition condition.

balloon, envelope). Also, enough additional animate nouns (e.g., chef, requiring a *yes* response) were included to create equal numbers of *yes* and *no* responses in each list. In total, 148 of the filler items in each list were inanimate and 24 were animate.

Stimuli for the Symbol/Shape task

Shapes were defined as having no extrinsic meaning (e.g., circle, square), whereas symbols were defined as shapes that convey meaning beyond their own identity (e.g., dollar sign, musical note). Symbols and shapes were generated from standard fonts (Symbol MT, Webdings, Webdings 1, Webdings 2, Webdings 3, and Cambria Math). Forty-four shapes and 44 symbols were pretested to 15 University of California San Diego undergraduate students to ensure appropriate classification. Shapes and symbols were equal in size (640 × 480 ppi). Items were presented in black and white, one at a time, and participants made a symbol or shape judgment for each. Only items that achieved 75% consistency in categorization were included in the study. The average ratings were 96.8% (SD = 9%) for shapes and 96.1% (SD = 10%) for symbols. An example of the symbols and shapes used is presented in Figure 4.

Stimuli for the Symbol/Attneave task

The symbols used in this task were identical to those used in the Symbol/Shape task. Instead of shapes, however, the contrast condition was nonidentifiable shapes known as Attneaves (Attneave, 1957; Vanderplas & Garvin, 1959; see Figure 4 for examples). These shapes are not nameable, have no inherent meaning, and have been used successfully in the literature to investigate language processing (e.g., Sehyr, Nicodemus, Petrich, & Emmorey, 2018). The task structure was the same for the Symbol/Attneave task as for the Symbol/Shape task.

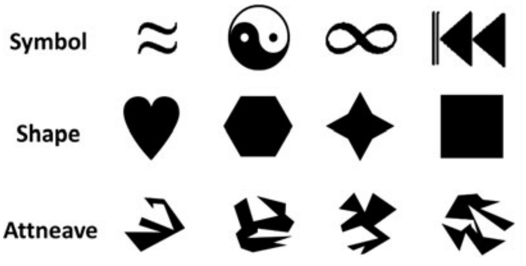

Figure 4. Examples of stimuli used for the Symbol/Shape Decision and Symbol/Attneave Decision tasks.

Equipment and setting

All testing was conducted in a quiet room in the Language and Neuroscience Group Laboratory at San Diego State University. Experimental protocols were presented on desktop PCs with 21-in. monitors connected with two-button response boxes. Tempo (ver. 2.1.5) software, a program developed at the University of California San Diego (Callahan, Walenski, & Love, 2012; Ferrill, Love, Walenski, & Shapiro, 2012; Love, Walenski, & Swinney, 2009; Sullivan, Walenski, Love, & Shapiro, 2017) controlled the timed presentation of the visual stimuli and the collection of participant responses (both YES/NO decisions and millisecond accurate reaction times for each decision). Responses were made using a two-button response box and were recorded if they were made while the stimulus was still presented on the computer monitor; any responses made after the stimulus disappeared were not recorded and were counted as "no response." As shown in Figure 2, all stimuli were presented in a continuous fashion.

Experimental protocol

After the initial evaluation was completed, with the assessments outlined previously, each participant was seen for six experimental sessions per task, with only one task and one interstimulus condition (500, 1,000, or 1,500) presented in any given session. There was a minimum of 1 week in between testing sessions. The order of list presentation for any given task was balanced across participants using a 3 × 3 Latin Square design. Participation in all tasks and conditions required 24 individual testing sessions (six visits for each of the four tasks), but this was not possible for all participants. Because data were analyzed only for participants who contributed to all ISI conditions within a task, a list of which tasks each participant contributed to is included in Table 1.

For the experimental task, participants were seated at a comfortable distance from a computer monitor and were told that they would be seeing items presented on the computer screen one at a time in a continuous fashion; for the Lexical Decision and Semantic Decision tasks, they were told that they would see letter strings; for the Symbol/Shape and Symbol/Attneave tasks, they were told that they would see pictures. Participants were instructed as to the binary decision they were to make via a two-button response box (word/nonword; alive/not alive; symbol/shape). Participants were told that the items would be on the screen for a short period of time and that they were to make their decision as quickly, yet accurately, as possible. They first practiced making the binary decisions "offline" as they were presented with 10 individual 3 × 5 index cards containing stimuli not included in the computer task. Half the items required a right button response whereas the other half required a left button response. This offline practice allowed the experimenter time to work with the participants, providing feedback as needed, and ensure that they understood the distinction to be made. Once complete, participants began the "online" portion of the study, with the Lexical Decision, Semantic Decision, Symbol/Shape, and Symbol/Attneave tasks. At the beginning of each experimental session, practice items were first presented to ensure that the participant could perform the task accurately on the computer. An additional break was provided after the first practice items to ensure that the participant understood the task and was willing to continue with it at that time.

For the Lexical Decision and Semantic Decision tasks, the 378 items in each experiment list were divided into three blocks of 126 items each so that participants could take breaks over the course of the session (see Table 3). Each block began with 10 practice items, as described previously, to ensure participant understanding of the task. Following this practice period, items within each list were pseudorandomized, with experimental word pairs separated by filler and repetition items so as to reduce awareness of the pairings. For example, there were never two prime-target pairs from the same condition (e.g., semantically related or semantically unrelated) presented consecutively. Each target word for each semantic or repetition prime pair was seen twice at every ISI, though never in the same session; words that were shown in one list in a given ISI preceded by a

Table 3. Distribution of items included in a single experimental list, as presented at each of the three interstimulus intervals in the Lexical Decision and Semantic Decision tasks[a]

No. of Items	Block 1	Block 2	Block3
Practice (5 words/ 5 nonwords)	10	10	10
Prime: Target pairs	20	20	20
Related: "*dove-eagle*"	10 related pairs	10 related pairs	10 related pairs
Unrelated: "*dock-eagle*"	10 unrelated pairs	10 unrelated pairs	10 unrelated pairs
Filler	58	58	58
Nonrepetition	6	6	6
Repetition	6 (prime) + 6 (target)	6 (prime) + 6 (target)	6 (prime) + 6 (target)
Total	126	126	126

[a]There were two lists for each interstimulus interval to control for the related and unrelated conditions. Each list was divided into three blocks of 126 items per block, with 10 practice items at the start of each block.

semantic or repetition prime were included in the other list preceded by their unrelated primes (note that this was true for all tasks). Thus, the two lists within each ISI condition contained the same target words but in different prime conditions, as shown in Figure 2. Filler nonwords were the same in each version of a list within a given ISI. Finally, prime-target word pairs that occurred early for some participants were placed late for other participants to balance potential effects of fatigue.

Lists for the Symbol/Shape and Symbol/Attneave decision tasks were structured largely in the same way as described for the Lexical Decision and Semantic Decision tasks, except that all prime-target pairs involved repetition priming, with the prime matching the target. This use of repetition primes allowed assessment of the time course of priming effects despite there being no way to determine or define semantic relationships between shapes or symbols.

As with the Lexical Decision and Semantic Decision tasks, six experimental lists were created (two for each ISI). Each list in the Symbol/Shape and Symbol/Attneave decision tasks contained 122 stimuli, which were distributed across related and unrelated shape or Attneave pairs, related and unrelated symbol pairs, and shape or Attneave and symbol fillers (see Table 4). Each target was preceded either by an identical shape/Attneave or symbol (the primed *repetition* condition) or by a different shape/Attneave or symbol (the unprimed *nonrepetition* condition; see Figure 2). Primed (repeated) and unprimed (nonrepeated) targets were distributed between lists, as described for the previous tasks. As in the Lexical Decision and Semantic Decision tasks, pre-experimental training and feedback were provided to ensure that participants understood the task and the decisions it required. Priming effects were calculated by comparing reaction times with the targets in the repeated versus nonrepeated conditions.

As shown in Figure 2, stimuli in all tasks were presented for 700 ms, with ISI varying between conditions. The response in all tasks was a binary button press on a two-button response box, executed by the participant's nondominant (L) hand. The dependent variable was the reaction time from target stimulus presentation to button press response.

Data processing and analysis

Reaction times (RTs; in milliseconds) for all correct button press responses to the target items were retrieved from Tempo (version 2.1.5) and trimmed to remove any responses faster than 200 ms, which was considered to be too fast to actually be responding to the stimulus. In addition, responses were removed if they fell greater than or less than 2 standard deviations from the mean for that participant in that condition; this eliminated data that might reflect anticipatory responses (too fast to be responsive to the stimulus) or responses made when the participant was

Table 4. Distribution of items included in experimental lists at each ISI for the Symbol/Shape Decision task and the Symbol/Attneave Decision task

Stimulus type	List 1	List 2
Practice (5 words/5 nonwords)	12 (4 repetition pairs + 4 nonrepetition items)	12 (4 repetition pairs + 4 nonrepetition items)
Repetition: shape or Attneave	15 (prime) + 15 (target)	15 (prime) + 15 (target)
Repetition: symbol	15 (prime) + 15 (target)	15 (prime) + 15 (target)
Nonrepetition: shape or Attneave	15	15
Nonrepetition: symbol	15	15
Fillers	20 (10 symbol + 10 shape)	20 (10 symbol + 10 shape)
Total	122	122

Table 5. Percent of data (and standard deviation) included in each analysis after screening for response accuracy and response time outliers

	LD	SD	SS Symbol	SS Shape	SA Symbol	SA Attneave
PWA	89% (10%) $n = 12$	74% (19%) $n = 8$	85% (13%) $n = 11$	86% (16%) $n = 11$	96% (5%) $n = 9$	96% (11%) $n = 9$
AMC	98% (2%) $n = 7$	96% (2%) $n = 5$	95% (3%) $n = 6$	89% (13%) $n = 6$	97% (4%) $n = 4$	98% (4%) $n = 4$

Note. AMC = age-matched neurotypical control; LD = Lexical Decision Task; PWA = people with aphasia; SA = Symbol/Attneave Task; SD = Semantic Decision Task; SS = Symbol/Shape Task.

distracted or otherwise not on task; for each group and each task (across all ISIs), 4%–5% of the data were removed for this reason. Additional details about the percentage of responses included in each analysis following the entire trimming process and the average RTs for related and unrelated stimuli and percentage of responses included for each person in each analysis are presented in Table 5 and Appendix A, Tables A1 to A6. The filler items were not analyzed as they were merely intended to provide a valid binary option for lexical/semantic decision and to prevent the participant from discovering the embedded experimental pairs. Prime items were not analyzed as they served simply to create the related and unrelated prime conditions for the targets.

Visual analysis of the trimmed data revealed that both groups approximated normal distributions. One of the participants with aphasia showed slower overall reaction times relative to their group but the priming effects found for that participant were within the typical range. Therefore, all analyses were conducted on nontransformed data. No effect was found on the visit number in which a task was presented, so this factor was not included in the analysis models. Analysis for response bias between yes and no responses for both the Lexical Decision and Semantic Decision tasks revealed that both groups were well above chance performance for both types of responses (see Table 6).

Data were analyzed using linear mixed-effects analyses. Within each task, mixed-effects models were created to evaluate the effects of priming in each ISI. Separate models were conducted for each ISI by group, as our predictions were based on specific patterns of effects in each condition. Analyses were performed using the lme4 package (Bates, Maechler, & Bolker, 2012) in R (R Core Team, 2013) and degrees of freedom were calculated using the Satterthwaite's (Kenward-Roger's) approximations for the *t* test and corresponding *p* values in the package lmerTest (Kuznetsova, Brockhoff, & Christensen, 2017). In each model, relatedness was included as a fixed effect and participant and item were entered as random effects on intercept terms. For these analyses, the models did not converge when random slopes were included; therefore, the following analyses contain the maximal random effects structure (Barr, Levy, Scheepers, & Tily, 2013).

Analyses for each task (Lexical Decision, Semantic Decision, Symbol/Shape and Symbol/Attneave) included only those participants who completed all six lists for that task. To alleviate concerns that results may differ across tasks due to different participants completing them, more limited analyses were conducted that included only those participants who contributed data to all four tasks (6 PWA and 3 AMC participants); no differences in priming patterns were seen compared with analyses of the full data set so that all participants are reported in the analyses presented later.

Initial analyses compared response times for related and unrelated targets in each task

Table 6. Comparison of response accuracy against chance for both groups on the Lexical Decision and Semantic Decision tasks

Group	Task	Target Response/Condition	Average % Correct	*t*	*p*
AMC	Lexical Decision	Yes—related	99	115.1	<.001
	($df = 6$)	Yes—unrelated	98	63.8	<.001
		No—fillers	97	65.1	<.001
	Semantic Decision	Yes—related	95	49.5	<.001
	($df = 4$)	Yes—unrelated	96	75.6	<.001
		No—fillers	82	20.1	<.001
PWA	Lexical Decision	Yes—related	89	12.1	<.001
	($df = 6$)	Yes—unrelated	89	16.9	<.001
		No—fillers	78	4.5	.001
	Semantic Decision	Yes—related	72	3.42	.011
	($df = 4$)	Yes—unrelated	72	3.29	.013
		No—fillers	76	9.04	<.001

Note. AMC, age-matched neurotypical control; PWA, people with aphasia.

at each ISI for PWA and for AMC participants. For the Lexical Decision and Semantic Decision tasks, both repetition and semantic priming were analyzed, whereas the Symbol/Shape and Symbol/Attneave tasks involved only repetition priming.

RESULTS

Verification of task manipulation

It is well established that more complex tasks involve deeper processing (Craik & Lockhart, 1972; Love et al., 2006). In addition, semantic activation occurs after analysis and recognition of word form (Grainger & Holcomb, 2009; Levelt, 2001), indicating that semantic access is more complex than word recognition. Therefore, to support our supposition that the tasks used in this experiment recruited different levels and degrees of linguistic processing, an analysis of variance was conducted to compare the effect of task type on reaction times in each of the four tasks. Results showed a significant main effect of task on mean reaction times, $F(5,30239) = 375.1$, $p < .001$ (see Table 7). Follow-up comparisons using a Tukey test showed significant differences ($p \leq .001$) in all pairwise comparisons when controlling for family-wise error rate at $p < .05$.

Assessment of priming effects

Priming effects were defined as the presence of significantly faster reaction times when targets were immediately preceded by related primes versus unrelated primes in the Lexical Decision and Semantic Decision tasks or by a repetition prime versus unrelated

Table 7. Mean reaction times and standard deviations for each repetition priming task, averaged across participants in both groups and all interstimulus interval conditions

Task	Mean RT, ms	*SD*, ms
SA Attneave	558.54	164.97
SA Symbol	589.12	202.10
SS Shape	604.37	188.96
SS Symbol	622.68	195.13
LD	665.00	198.38
SD	711.89	235.09

Note. LD = Lexical Decision Task; SA = Symbol/Attneave Task; SD = Semantic Decision Task; SS = Symbol/Shape Task.

prime in all tasks. Both repetition priming and semantic priming effects were analyzed.

Repetition priming effects

For repetition priming in the Lexical Decision and Semantic Decision tasks, AMC participants showed significant priming across all ISIs and conditions. The same pattern was found for the overall PWA group (see Table 8) and also held true when agrammatic and nonagrammatic PWA were analyzed separately (see Table 9). For repetition priming in the Symbol/Shape and Symbol/Attneave tasks, the group data from the AMC participants, agrammatic PWA, and nonagrammatic PWA all similarly demonstrated repetition priming across all ISIs.

Semantic priming effects

The effects of increased linguistic demand on automatic spreading activation were explored by analyzing the semantic priming conditions in the Lexical Decision and Semantic Decision tasks. As shown in Table 10, AMC participants, as a group, showed significant priming effects for both tasks in the 500 ms ISI. In addition, they showed priming in the 1,000-ms ISI condition for the Lexical Decision task, and in the 1,500-ms ISI condition for the Semantic Decision task. People with aphasia, as a group, showed significant priming in the 500- and 1,000-ms ISI conditions only for the Lexical Decision task. Individual data are presented for all participants in Appendix A.

Because prior research has shown differential time courses for priming effects between PWA who are agrammatic and those who are nonagrammatic (e.g., Poirier, Shapiro, Love, & Grodzinsky, 2009; Sheppard, Love, Midgley, Holcomb, & Shapiro, 2017), post hoc analyses were conducted to assess these subgroups (see Table 11). Consistent with prior reports, *in the Lexical Decision task*, participants who were agrammatic showed significant priming in the 1,500-ms ISI condition whereas nonagrammatic PWA participants, as a group, showed priming in the 500- and 1,000-ms ISI conditions but not in the 1,500-ms ISI condition. Despite considerable variability in the size of priming effects, univariate analysis of variance revealed that there was no significant difference between the four nonagrammatic PWA in their priming effects in the 500-ms ISI condition, $F(3) = 2.15$, $p = .095$, or the 1,500-ms ISI condition, $F(3) = 1.326$, $p = .267$. There was a significant difference between participants in the 1,000-ms ISI condition, $F(3) = 4.908$, $p = .003$, although all participants showed effects in the same direction (i.e., average RTs for related items were faster than average RTs for unrelated items). *In the Semantic Decision task*, neither subgroup showed significant priming.

DISCUSSION

This study investigated learning in aphasia through exploring the time course of priming effects in PWA, as compared with AMC, across tasks that included both linguistic and nonlinguistic stimuli and required a range of linguistic and minimally linguistic processing. Tasks included both repetition priming and semantic priming components, which are discussed here in turn. We had predicted that PWA would show altered patterns of activation in the semantic priming task, with an interaction with task requirements based on the level of linguistic processing required, and that they might show altered activation across both linguistic and nonlinguistic tasks.

Contrary to our expectation that there may be altered activation in nonlinguistic tasks, significant repetition priming effects were obtained for both groups for all nonorthographic tasks (Symbol/Shape and Symbol/Attneave) at all ISIs. In addition, both groups showed repetition priming effects in the context of the Lexical Decision and Semantic Decision tasks, with faster responses to repeated presentation of written words than to those same words when they were presented without an identity prime. This pattern was expected for the AMC participants but was unexpected for the PWA, who were expected to show delayed or absent priming for

Table 8. Summary of repetition priming effects (in ms, Repeated–Unrepeated) for all interstimulus interval conditions and all tasks for all AMC participants and all PWA[a]

		AMC				PWA		
Task	***n***	**500**	**1,000**	**1,500**	***n***	**500**	**1,000**	**1,500**
LD	$n = 7$	−69.1[b]	−65.6[b]	−72.7[b]	$n = 12$	−61.6[b]	−60.4[b]	−77.9[b]
		$t = -9.71$	$t = -8.92$	$t = -10.85$		$t = -7.06$	$t = -6.86$	$t = -8.42$
		$p < .001$	$p < .001$	$p < .001$		$p < .001$	$p < .001$	$p < .001$
SD	$n = 5$	−125.9[b]	−146.2[b]	−128.8[b]	$n = 8$	−124.4[b]	−127.6[b]	−139.8[b]
		$t = -13.79$	$t = -16.17$	$t = -15.08$		$t = -11.11$	$t = -9.40$	$t = -9.14$
		$p < .001$	$p < .001$	$p < .001$		$p < .001$	$p < .001$	$p < .001$
SS Symbol	$n = 6$	−108.38[b]	−106.15[b]	105.61[b]	$n = 11$	−145.43[b]	−132.89[b]	−110.36[b]
		$t = -14.00$	$t = -13.18$	$t = -12.19$		$t = -15.97$	$t = -13.31$	$t = -11.08$
		$p < .001$	$p < .001$	$p < .001$		$p < .001$	$p < .001$	$p < .001$
SS Shape	$n = 6$	−103.49[b]	−108.94[b]	−127.62[b]	$n = 11$	−99.98[b]	−135.25[b]	−171.21[b]
		$t = 14.88$	$t = -11.08$	$t = -8.14$		$t = -11.58$	$t = -14.71$	$t = -15.53$
		$p < .001$	$p < .001$	$p < .001$		$p < .001$	$p < .001$	$p < .001$
SA Attneave	$n = 4$	−65.74[b]	−47.25[b]	−47.82[b]	$n = 9$	−83.07[b]	−66.28[b]	−36.54[b]
		$t = 13.45$	$t = -6.00$	$t = -5.78$		$t = -10.04$	$t = -9.81$	$t = -5.98$
		$p < .001$	$p < .001$	$p < .001$		$p < .001$	$p < .001$	$p < .001$
SA Symbol	$n = 4$	−78.40[b]	−76.71[b]	−67.70[b]	$n = 9$	−94.05[b]	−88.10[b]	−80.73[b]
		$t = -9.24$	$t = -9.15$	$t = -7.93$		$t = -11.38$	$t = -13.25$	$t = -8.89$
		$p < .001$	$p < .001$	$p < .001$		$p < .001$	$p < .001$	$p < .001$

[a]Note that difference scores presented here reflect model output from the mixed model regression analysis, not raw RT differences.
[b]Statistical significance at $p = 0.05$. Symbol, Shape, and Attneave data are reported separately to account for any differences that may have occurred based on task context.

Table 9. Summary of repetition priming effects (in ms, Repeated–Unrepeated) for all interstimulus interval conditions and all tasks for non-agrammatic versus agrammatic PWA[a]

		Nonagrammatic PWA				Agrammatic PWA		
Task	***n***	**500**	**1,000**	**1,500**	***n***	**500**	**1,000**	**1,500**
LD	$n = 4$	-92.1[b]	-118.6[b]	-108[b]	$n = 8$	-43.2[b]	-29.4[b]	-64[b]
		$t = -7.28$	$t = -10.69$	$t = -11.58$		$t = -3.71$	$t = -2.42$	$t = -4.83$
		$p < .001$	$p < .001$	$p < .001$		$p < .001$	$p = .02$	$p < .001$
SD	$n = 2$	-143.2[b]	-163.9[b]	-102.5[b]	$n = 6$	-114.5[b]	-111[b]	-152.3[b]
		$t = -6.96$	$t = -10.28$	$t = -4.97$		$t = -9.07$	$t = -6.52$	$t = -8.02$
		$p < .001$	$p < .001$	$p < .001$		$p < .001$	$p < .001$	$p < .001$
SS Symbol	$n = 4$	-146.1[b]	-151[b]	-96.5[b]	$n = 7$	-143.24[b]	-123.45[b]	-118.71[b]
		$t = -11.93$	$t = -13.29$	$t = -10.02$		$t = -11.28$	$t = -8.41$	$t = -8.41$
		$p < .001$	$p < .001$	$p < .001$		$p < .001$	$p < .001$	$p < .001$
SS Shape	$n = 4$	-145.9[b]	-139.11[b]	-127.62[b]	$n = 7$	-77.71[b]	-135.65[b]	-188.02[b]
		$t = -9.73$	$t = -10.54$	$t = -9.16$		$t = -7.28$	$t = -11.06$	$t = -8.12$
		$p < .001$	$p < .001$	$p < .001$		$p < .001$	$p < .001$	$p < .001$
SA Attneave	$n = 2$	-117.73[b]	-83.17[b]	-41.22[b]	$n = 7$	-69.23[b]	-61.34[b]	-37.917[b]
		$t = -7.58$	$t = -5.77$	$t = -3.36$		$t = -7.47$	$t = -8.08$	$t = -5.02$
		$p < .001$	$p < .001$	$p = 001$		$p < .001$	$p < .001$	$p < .001$
SA Symbol	$n = 2$	-77.89[b]	-68.43[b]	-62.02[b]	$n = 7$	-97.33[b]	-93.2[b]	-86.32[b]
		$t = -7.32$	$t = -6.28$	$t = -5.87$		$t = -9.56$	$t = -11.84$	$t = -7.57$
		$p < .001$	$p < .001$	$p < .001$		$p < .001$	$p < .001$	$p < .001$

Note. LD = Lexical Decision Task; PWA = people with aphasia; SA = Symbol/Attneave Task; SD = Semantic Decision Task; SS = Symbol/Shape Task.
[a]Note that difference scores presented here reflect model output from the mixed model regression analysis, not raw RT differences.
[b]Statistical significance at $p = 0.05$. Symbol, Shape, and Attneave data are reported separately to account for any differences that may have occurred based on task context.

Table 10. Summary of semantic priming effects (in ms, Related–Unrelated) across all interstimulus interval conditions in the Lexical Decision and Semantic Decision tasks for all AMC participants and all PWA[a]

		AMC				PWA		
Task	***n***	**500**	**1,000**	**1,500**	***n***	**500**	**1,000**	**1,500**
LD	$n = 7$	−11.8[b]	−11.2[b]	0.9	$n = 12$	−10.1[b]	−13.4[b]	−6.96
		$t = 2.45$	$t = 2.22$	$t = -0.23$		$t = 2.14$	$t = 2.10$	$t = 1.9$
		$p = .01$	$p = .03$	$p = .81$		$p = .03$	$p = .03$	$p = .06$
SD	$n = 5$	−18.42[b]	−3.95	−23.53[b]	$n = 8$	−2.1	0.4	−12.2
		$t = 2.51$	$t = 0.67$	$t = 3.2$		$t = -0.31$	$t = 0.85$	$t = 1.04$
		$p = .01$	$p = .50$	$p < .001$		$p = .75$	$p = .40$	$p = .30$

Note. AMC = age-matched neurotypical control; LD = Lexical Decision Task; PWA = people with aphasia; SD = Semantic Decision Task; SS = Symbol/Shape Task.
[a]Note that difference scores presented here reflect model output from the mixed model regression analysis, not raw RT differences.
[b]Statistical significance at $p = .05$.

tasks that included linguistic stimuli and for whom we expected the possibility that there would be some difference for nonlinguistic tasks, as well. These results indicate that learning, in its most basic form as reflected by repetition priming effects, is unimpaired in PWA; specifically, the PWA showed no differences from the age-matched controls in automatic spreading activation on tasks that required minimal language processing and, importantly, this remained true even with orthographic stimuli (i.e., words), which require higher levels of linguistic processing. Participants in both groups demonstrated that they successfully perceived visual stimuli (whether symbols, shapes, or written words) and that prior exposure is enough to allow for a faster response time upon subsequent presentation of the same item. Keeping in mind that the repetition priming condition

Table 11. Summary of semantic priming effects (in ms, Related–Unrelated) across all interstimulus interval conditions in the Lexical Decision and Semantic Decision tasks for non-agrammatic versus agrammatic PWA[a]

		Nonagrammatic PWA				Agrammatic PWA		
Task	***n***	**500**	**1,000**	**1,500**	***n***	**500**	**1,000**	**1,500**
LD	$n = 4$	−17.8[b]	−25.7[b]	4.6	$n = 8$	−5.1	−6.4	−13.7[b]
		$t = 2$	$t = 2.34$	$t = -0.16$		$t = 1.22$	$t = 1.10$	$t = 2.04$
		$p = .04$	$p = .02$	$p = .87$		$p = .22$	$p = .28$	$p = .04$
SD	$n = 2$	−18	6	8.6	$n = 6$	5.6	−0.9	−30.6
		$t = 1.04$	$t = -0.35$	$t = -0.55$		$t = -1.19$	$t = 1.77$	$t = 1.45$
		$p = .30$	$p = .72$	$p = .59$		$p = .23$	$p = .24$	$p = .15$

Note. LD = Lexical Decision Task; PWA = people with aphasia; SD = Semantic Decision Task.
[a]Note that difference scores presented here reflect model output from the mixed model regression analysis, not raw RT differences.
[b]Statistical significance at $p = .05$.

was included as a way to understand the relative impairment or integrity of linguistic versus domain-general cognitive processes in aphasia, these findings suggest that automatic spreading activation, a fundamental mechanism of cognitive processing, remains intact in PWA across cognitive and linguistic domains.

The semantic priming effects for the Lexical Decision and Semantic Decision tasks, however, showed different patterns of results relative to the repetition priming condition. First, replicating prior research (e.g., Stern, Prather, Swinney, & Zurif, 1991) *on the Lexical Decision task*, the AMC participants, as a group, showed significant priming effects at the shortest and middle ISIs but not at the longest. This means that the activation initiated in the linguistic system from seeing the prime word spread to semantically related words, including the target, quickly. Thus, by the time the target was presented 500 or 1,000 ms after the prime, the semantically related target words were more highly activated and, therefore, easier to recognize than when they were presented without an unrelated prime. In contrast, by 1,500 ms after the prime was presented, this advantage was gone, indicating that the activation boost from the prime had dissipated. This pattern of performance replicates prior work showing priming at short ISIs, followed by dissipation of priming effects at longer ISIs in typical adults (Love & Swinney, 1996; Silkes & Rogers, 2012). The nonagrammatic PWA showed this same pattern, whereas the agrammatic PWA differed; that subgroup showed priming only at the longest interval. The semantic priming results from the Lexical Decision task are consistent with the Delayed Lexical Activation hypothesis, which suggests that the language-processing impairments of agrammatic aphasia are related to slowing of automatic spreading activation within the language networks (Love et al., 2008). This phenomenon has been demonstrated across numerous methods, including list priming (Prather et al., 1997), cross-modal lexical priming (Burkhardt, Pinango, & Wong, 2003; Haarmann & Kolk, 1991; Love et al., 2008; Love, Swinney, & Zurif, 2001), cross-modal picture priming (Ferrill et al., 2012), gaze patterns in response to auditory stimuli (Thompson & Choy, 2009), and neural responses in response to auditory stimuli (Sheppard et al., 2017). Impairment of automatic spreading activation across lexical items, as demonstrated here by a delay in priming effects with the introduction of a semantic relationship between prime and target, arguably hinders learning and processing in the linguistic system (Love et al., 2008; Prather et al., 1997; Silkes & Rogers, 2012).

On the Semantic Decision task, the AMC participants, as a group, again showed significant priming at the 500-ms ISI. They did not, however, show it at the 1,000-ms ISI but, interestingly, it appeared again at the 1,500-ms ISI. This latter effect was unexpected and may reflect that the priming effects at the shorter ISI were the result of automatic processes but that these participants used explicit, strategic processing to facilitate responses when longer time was provided. Both subgroups of PWA, however, showed performance that differed from the AMC participants, with no statistically significant priming effects obtained for either subgroup. This may suggest that the Semantic Decision task, which required explicitly engaging deep semantic representations (for the alive/not alive decision), interfered with the system's ability to automatically spread? unsure activation within the same semantic networks. This is in direct contrast to the Lexical Decision task, in which engaging at that shallower level of linguistic representation (for the word/nonword decision) did not interfere with automatic semantic priming effects. We do note, however, that individual patterns of performance suggest that there may be priming effects occurring for some of the individual participants, but variances were too high and/or there were not enough participants, leaving the analyses underpowered. For instance, the average priming effect for the agrammatic PWA in the 1,500-ms ISI condition on the Semantic Decision task is 30.6 ms, which is substantially larger than the priming effects obtained in other conditions but did not meet the criterion for statistical significance due to high variance. If this were to be borne out in a larger sample, it would be further supported for the presence of delayed lexical activation in this subgroup. In addition, both nonagrammatic participants showed effects in the direction of priming in the 500-ms condition, also with a relatively large average difference between primed and unprimed items. Despite them showing the same direction of effects, the small sample size obscured any significant effects that may be present and would reinforce the idea that priming effects for nonagrammatic PWA are similar to those of AMC participants. Future studies with more participants in both the agrammatic and nonagrammatic groups will be important to drawing firmer conclusions. With that said, the increased variability in the Semantic Decision task speaks to the increased complexity of that task and to the vulnerability of the semantic networks in aphasia when they are placed under heavy demands.

The tasks used in this study each engaged different degrees of language processing, as reflected by a hierarchy of response times across tasks. Responses to Attneave stimuli were fastest, symbols and shapes had intermediate response times (with the Symbol/Attneave task being faster overall than the Symbol/Shape task), the lexical decision task RTs were longer, and the semantic decision task RTs were the longest. This progression of RTs can be accounted for by considering the amount of time needed to engage progressively more levels of processing, validating the choice of tasks and our ability to interpret the outcomes. We argue that the patterns observed along the continuum of linguistic processing demands can be explained as reflecting differences in the ability to engage spreading activation within versus across items in the linguistic network. A repetition effect reflects facilitation *within* the processing pathway for a single item whereas, for semantic priming to occur, there needs to be spreading of activation *across* items at a deep level within the semantic network. For PWA, this semantic priming process is susceptible to interference based on other task demands.

CONCLUSION

The data presented here add to the body of literature that suggests that individuals with aphasia retain automatic spreading activation, although the time course within which it occurs may be different from neurotypical adults (Love et al., 2008; Prather et al., 1997; Silkes & Rogers, 2012), particularly for those with agrammatic aphasia. Importantly, this implies that PWA can learn using the same mechanisms of spreading activation that support learning in the typical system. These data suggest, however, that some PWA may not always process incoming linguistic information efficiently; in particular, this problem may increase with increasing complexity in the processing task, as the system recruits more widely-dispersed elements in the linguistic network.

This study is limited by its relatively small number of participants in each aphasia subgroup. Although this repeated-measures design provided a large amount of data for each participant, further investigation with larger samples would be worthwhile. In addition, the magnitude of priming responses in this study appears to be graded, with smaller responses as more linguistic processing is required to complete the target task. Future studies with larger samples may provide insights into whether this is a robust finding and should explore the factors that influence the magnitude of the responses obtained. This would also allow for investigation of individual differences.

This work has implications not only for understanding the underlying impairments of aphasia but also for aphasia treatment. Aphasia treatment involves both implicit and explicit learning, both of which rely on automatic spreading activation. If a person with aphasia has a system that spreads activation more slowly than typical, he or she may benefit from altered rates of presentation of stimuli or cues in a treatment context, as well as needing longer periods of time before a response is required after a stimulus is presented. In addition, knowing that repetition priming patterns are the same for both PWA and neurotypical adults for linguistic information supports the idea that repetition priming may be a useful tool for improving language processing in PWA. Further research is needed to fully outline and understand these parameters and how best to apply them to aphasia rehabilitation.

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Appendix A

Table A1. Average reaction times (with standard deviations) in milliseconds (ms) for each ISI condition on the Lexical Decision task, related and unrelated targets, and the percentage of data included after trimming for each (a) participant with aphasia (n = 12) and (b) age-matched control participant (n = 7) in each ISI condition in the Lexical Decision task

(a)

PWA

		Group Mean RT in ms and % Accuracy (*SD*)	LHD009	LHD019	LHD040	LHD101	LHD130	LH132	LHD138	LHD139	LHD142	LHD145	LHD146	LHD148
500-ms ISI	Related	698 (130)	540 (94)	790 (91)	833 (148)	721 (62)	690 (93)	562 (93)	657 (115)	649 (107)	692 (81)	1,003 (97)	570 (103)	671 (88)
	Unrelated	710 (119)	592 (119)	845 (91)	834 (160)	709 (59)	701 (78)	571 (98)	651 (117)	670 (119)	715 (142)	972 (133)	591 (87)	665 (81)
	% accuracy	87% (10%)	89%	90%	84%	97%	84%	96%	67%	94%	83%	71%	90%	98%
1,000-ms ISI	Related	719 (149)	625 (111)	929 (135)	750 (128)	811 (77)	579 (50)	527 (101)	736 (146)	722 (140)	728 (111)	1,020 (220)	541 (104)	663 (75)
	Unrelated	737 (141)	626 (90)	937 (108)	763 (127)	833 (95)	591 (63)	606 (140)	748 (119)	703 (125)	750 (127)	1,033 (219)	583 (98)	668 (77)
	% accuracy	90% (9%)	94%	96%	84%	100%	90%	100%	67%	87%	89%	87%	94%	98%
1,500-ms ISI	Related	734 (180)	659 (100)	1,001 (184)	751 (108)	723 (57)	620 (51)	539 (80)	689 (73)	658 (94)	679 (119)	1,162 (240)	555 (82)	773 (72)
	Unrelated	748 (206)	655 (117)	1,022 (161)	765 (147)	723 (41)	612 (66)	559 (78)	723 (108)	655 (102)	693 (134)	1,265 (309)	532 (74)	772 (74)
	% accuracy	90% (10%)	91%	91%	91%	100%	90%	97%	61%	96%	89%	83%	97%	99%

(b)

AMC

		Group Mean RT in ms and % Accuracy (*SD*)	AMC081	AMC109	AMC121	AMC126	AMC131	AMC150	AMC152
500-ms ISI	Related	544 (49)	550 (54)	474 (52)	565 (69)	627 (96)	538 (68)	551 (84)	502 (75)
	Unrelated	556 (54)	575 (63)	477 (66)	575 (71)	646 (98)	530 (59)	569 (81)	522 (79)
	% accuracy	98% (2%)	100%	97%	100%	94%	97%	98%	97%
1,000-ms ISI	Related	570 (61)	592 (76)	478 (59)	646 (87)	583 (73)	594 (94)	601 (67)	493 (82)
	Unrelated	581 (58)	610 (101)	524 (79)	643 (83)	613 (94)	589 (65)	611 (90)	478 (67)
	% accuracy	99% (1%)	100%	97%	99%	99%	98%	97%	99%
1,500-ms ISI	Related	549 (57)	564 (48)	468 (50)	604 (64)	551 (55)	574 (72)	609 (86)	476 (71)
	Unrelated	548 (50)	566 (45)	495 (66)	607 (79)	543 (56)	570 (62)	586 (85)	468 (65)
	% accuracy	98% (1%)	100%	99%	98%	97%	99%	98%	97%

Note. AMC = age-matched neurotypical control; ISI = interstimulus interval; PWA = people with aphasia; RT = reaction time.

Table A2. Average reaction times (with standard deviations) in each ISI condition on the Semantic Decision task, in milliseconds (ms), for related and unrelated targets, and the percentage of data included after trimming for (a) each participant with aphasia ($n = 8$) and (b) each age-matched control participant ($n = 5$)

(a)

PWA

		Group Mean RT in ms and % Accuracy (*SD*)	LHD009	LHD019	LHD101	LHD130	LHD138	LHD139	LHD140	LHD146
500-ms ISI	Related	757 (105)	764 (131)	944 (92)	715 (79)	685 (100)	687 (60)	764 (146)	873 (163)	626 (106)
	Unrelated	755 (115)	782 (116)	970 (105)	692 (75)	672 (92)	669 (107)	735 (132)	879 (140)	646 (121)
	% accuracy	69% (20%)	72%	66%	96%	67%	34%	93%	57%	68%
1,000-ms ISI	Related	786 (157)	722 (109)	1,141 (195)	791 (87)	662 (78)	723 (80)	720 (124)	861 (228)	671 (136)
	Unrelated	796 (154)	728 (120)	1,115 (190)	791 (95)	682 (98)	719 (90)	740 (129)	935 (196)	657 (136)
	% accuracy	76% (16%)	84%	72%	97%	69%	43%	90%	77%	78%
1,500-ms ISI	Related	812 (174)	823 (137)	1,137 (314)	799 (94)	653 (70)	727 (89)	757 (140)	987 (215)	614 (115)
	Unrelated	826 (196)	814 (140)	1,145 (245)	807 (82)	680 (80)	703 (56)	754 (104)	1,100 (329)	603 (97)
	% accuracy	76% (22%)	87%	59%	99%	70%	34%	98%	79%	83%

(b)

AMC

		Group Mean RT in ms and % Accuracy (*SD*); $n = 5$	AMC081	AMC121	AMC126	AMC131	AMC152
500-ms ISI	Related	594 (66)	633 (80)	579 (97)	622 (99)	651 (73)	486 (53)
	Unrelated	613 (60)	652 (85)	594 (74)	637 (108)	663 (93)	517 (70)
	% accuracy	95% (3%)	92%	98%	93%	99%	93%
1,000-ms ISI	Related	612 (61)	625 (76)	606 (79)	645 (107)	670 (108)	512 (56)
	Unrelated	613 (61)	668 (96)	622 (81)	614 (82)	649 (110)	511 (67)
	% accuracy	96% (1%)	95%	97%	95%	97%	96%
1,500-ms ISI	Related	614 (45)	624 (78)	635 (80)	598 (78)	667 (104)	547 (77)
	Unrelated	640 (57)	676 (153)	650 (82)	619 (81)	700 (146)	553 (71)
	% accuracy	96% (2%)	94%	97%	98%	97%	97%

Note. AMC = age-matched neurotypical control; ISI = interstimulus interval; PWA = people with aphasia; RT = reaction time.

Table A3. Average reaction times in milliseconds (ms) for related and unrelated Symbol targets, and the percentage of data included after trimming, for (a) each participant with aphasia ($n = 11$) and (b) each age-matched control participant ($n = 6$) in each ISI condition in the Symbol/Shape Decision task

(a)

PWA

		Group Mean RT (in ms) and % Accuracy (*SD*)	**LHD009**	**LHD019**	**LHD040**	**LHD130**	**LHD132**	**LHD138**	**LHD139**	**LHD142**	**LHD145**	**LHD146**	**LHD148**
500-ms ISI	"prime"	661 (114)	565	875	622	604	583	638	717	591	874	567	637
	"target"	519 (104)	432	667	498	496	462	546	505	499	740	369	491
	% accuracy	84% (7%)	83%	84%	81%	90%	90%	87%	79%	83%	69%	83%	97%
1,000-ms ISI	"prime"	678 (162)	559	1,024	633	541	594	643	698	625	930	498	712
	"target"	550 (123)	437	748	556	448	506	565	602	559	770	364	497
	% accuracy	83% (15%)	87%	86%	93%	97%	93%	50%	72%	80%	64%	97%	93%
1,500-ms ISI	"prime"	688 (191)	563	1,057	732	506	593	588	712	506	968	521	820
	"target"	577 (172)	501	833	597	450	531	475	500	474	940	380	670
	% accuracy	88% (14%)	97%	97%	93%	97%	93%	87%	87%	83%	90%	97%	47%

(b)

AMC

		Group Mean RT (in ms) and % Accuracy (*SD*)	**AMC081**	**AMC109**	**AMC121**	**AMC126**	**AMC131**	**AMC150**
500-ms ISI	"prime"	549 (75)	589	427	566	646	507	560
	"target"	438 (50)	467	342	475	468	438	439
	% accuracy	93% (4%)	93%	97%	93%	86%	93%	97%
1,000-ms ISI	"prime"	553 (58)	631	457	555	582	561	532
	"target"	447 (46)	453	379	484	415	506	446
	% accuracy	95% (5%)	93%	93%	97%	97%	93%	97%
1,500-ms ISI	"prime"	579 (60)	615	481	662	573	560	581
	"target"	472 (84)	492	377	614	410	503	439
	% accuracy	97% (3%)	93%	100%	97%	93%	100%	97%

Note. AMC = age-matched neurotypical control; ISI = interstimulus interval; PWA = people with aphasia; RT = reaction time.

Table A4. Average reaction times in milliseconds (ms) for related and unrelated Shape targets, and the percentage of data included after trimming, for (a) each participant with aphasia ($n = 11$) and (b) each age-matched control participant ($n = 6$) in each ISI condition in the Symbol/Shape Decision task

(a)

PWA

		Group Mean RT (ms) and % Accuracy (*SD*)	LHD009	LHD019	LHD040	LHD130	LHD132	LHD138	LHD139	LHD142	LHD145	LHD146	LHD148
500-ms ISI	"prime"	621 (75)	533	692	735	596	619	544	709	562	697	541	597
	"target"	511 (96)	403	669	549	511	461	477	507	530	674	364	476
	% accuracy	90% (10%)	69%	100%	86%	83%	87%	83%	93%	100%	97%	96%	100%
1,000-ms ISI	"prime"	658 (111)	542	815	726	599	559	671	741	537	835	540	669
	"target"	525 (87)	434	644	570	532	493	552	565	448	667	385	484
	% accuracy	85% (20%)	70%	100%	96%	87%	100%	33%	97%	97%	76%	90%	93%
1,500-ms ISI	"prime"	698 (207)	587	1,120	729	573	647	541	673	494	1,061	552	697
	"target"	537 (122)	433	727	595	504	572	481	458	409	749	387	590
	% accuracy	83% (16%)	80%	90%	90%	80%	87%	90%	97%	90%	57%	100%	50%

(b)

AMC

		Group Mean RT (in ms) and % Accuracy (*SD*)	AMC081	AMC109	AMC121	AMC126	AMC131	AMC150
500-ms ISI	"prime"	558 (132)	580	500	478	816	503	470
	"target"	442 (68)	452	399	424	570	428	379
	% accuracy	88% (14%)	93%	80%	97%	63%	96%	100%
1,000-ms ISI	"prime"	552 (55)	606	529	521	637	508	514
	"target"	439 (37)	438	412	492	450	456	384
	% accuracy	88% (15%)	90%	69%	100%	70%	100%	100%
1,500-ms ISI	"prime"	551 (55)	538	527	526	662	538	513
	"target"	464 (32)	449	427	457	522	471	458
	% accuracy	89% (12%)	93%	72%	93%	77%	100%	100%

Note. AMC = age-matched neurotypical control; ISI = interstimulus interval; PWA = people with aphasia; RT = reaction time.

Table A5. Average reaction times in milliseconds (ms) for related and unrelated targets in the Symbol/Attneave Decision task, and the percent of data included after trimming, for each participant with aphasia (n = 9) at each ISI in the (a) the Attneave condition and (b) the Symbol condition

(a)

PWA

			Attneave								
		Group Mean % Accuracy (*SD*)	**LHD009**	**LHD019**	**LHD040**	**LHD101**	**LHD130**	**LHD138**	**LHD139**	**LHD140**	**LHD146**
500-ms ISI	"prime"		513	743	667	595	488	522	547	652	482
	"target"		449	625	617	548	463	433	439	591	308
	% accuracy	91% (19%)	100%	100%	100%	93%	45%	100%	100%	90%	100%
1,000-ms ISI	"prime"		477	739	660	733	512	553	554	519	478
	"target"		427	652	567	696	527	438	455	499	362
	% accuracy	99% (2%)	100%	100%	100%	100%	93%	100%	100%	97%	100%
1,500-ms ISI	"prime"		499	486	633	436	500	628	538	701	436
	"target"		495	722	610	755	488	530	469	672	353
	% accuracy	99% (2%)	97%	79%	100%	100%	97%	100%	100%	97%	97%

(b)

PWA

			Symbol								
		Group Mean % Accuracy (*SD*)	**LHD009**	**LHD019**	**LHD040**	**LHD101**	**LHD130**	**LHD138**	**LHD139**	**LHD140**	**LHD146**
500-ms ISI	"prime"		535	878	665	612	507	559	546	648	442
	"target"		492	629	552	554	448	417	529	624	331
	% accuracy	99% (2%)	93%	97%	97%	97%	90%	97%	100%	93%	93%
1,000-ms ISI	"prime"		514	900	634	703	515	637	585	515	447
	"target"		492	672	556	647	447	560	482	438	337
	% accuracy	96% (4%)	100%	97%	97%	97%	86%	97%	100%	97%	100%
1,500-ms ISI	"prime"		577	1,090	658	742	487	599	584	760	446
	"target"		549	747	645	694	442	516	501	752	352
	% accuracy	96% (7%)	79%	100%	100%	97%	100%	100%	97%	97%	79%

Note. ISI = interstimulus interval; PWA = people with aphasia.

Table A6. Average reaction times in milliseconds (ms) for related and unrelated targets in the Symbol/Attneave Decision task, and the percent of data included after trimming, for each age-matched control participant ($n = 4$) at each ISI in the Attneave and Symbol conditions

AMC			Attneave				Symbol			
		Group Mean % Accuracy (*SD*)	AMC121	AMC126	AMC131	AMC152	AMC121	AMC126	AMC131	AMC152
500-ms ISI	"prime"		546	484	550	372	529	529	535	453
	"target"		420	410	528	315	422	388	552	366
	% accuracy	Attneave: 96% (6%) Symbol: 97% (5%)	87%	100%	100%	97%	100%	97%	100%	90%
1,000-ms ISI	"prime"		492	484	491	388	522	514	508	471
	"target"		415	448	466	334	417	395	507	384
	% accuracy	Attneave: 99% (2%) Symbol: 97% (5%)	100%	100%	100%	97%	97%	100%	100%	90%
1,500-ms ISI	"prime"		514	503	528	398	513	471	544	466
	"target"		442	455	492	364	429	409	508	389
	% accuracy	Attneave: 99% (2%) Symbol: 98% (3%)	97%	100%	100%	100%	100%	100%	97%	93%

Note. AMC = age-matched neurotypical control; ISI = interstimulus interval; PWA = people with aphasia.