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PAPER

# Integrity of input verbal short-term memory ability predicts naming accuracy in aphasia

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**ABSTRACT**

**Background:** Contemporary models of aphasia predominantly attribute lexical retrieval deficits to impaired access and/or maintenance of semantic, lexical, and phonological representations of words. A central hypothesis of language-emergent models of verbal short-term memory (STM) is that temporary storage and maintenance of verbal information arises from activation of linguistic representations in long-term memory. This close relationship between short-term retention and linguistic representations has prompted accounts of aphasia that include impairments to both these components.

**Aims:** We investigated associations between measures of input semantic and phonological verbal STM and corresponding output processing measures. We hypothesised that both input and output functions of verbal STM rely on a common substrate (i.e., temporary activation and maintenance of long-term linguistic representations).

**Methods & Procedure:** Twenty adults with aphasia completed a series of semantic and phonological probe spans. Results were compared with naming performance in immediate and delayed conditions. The data were analysed using correlations, principal components analysis and linear regressions.

**Results & Discussion:** Input semantic and phonological verbal STM abilities were predictive of naming accuracy. Greater input semantic and phonological STM spans were associated with fewer semantic and phonological naming errors. Latent factors identified by principal components analysis of probe span data were consistent with a two-step interactive model of word retrieval. Probe spans measuring access to semantic and initial consonant-vowel representations aligned with lexical-semantic abilities (lexical-semantic factor). Probe spans assessing access to the rhyme component of a word measured lexical-phonological abilities (lexical-phonological factor). The principal components analysis indicated that stronger lexical-semantic abilities were associated with fewer semantic and nonword errors, and stronger lexical phonological abilities were associated with fewer formal and unrelated errors. In addition, our results were consistent with models that postulate serial access to phonology, proceeding from initial to final phonemes. The span

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measuring access to initial consonant-vowel was associated with lexical selection, while the span measuring access to rhyme information was associated with phonological selection.
**Conclusion:** Performance on input semantic and phonological tasks predicts accuracy of picture naming performance and types of errors made by people with aphasia. These results indicate overlap in input and output semantic and phonological processing, which must be accounted for in models of lexical processing. These findings also have implications for approaches to diagnosis and treatments for lexical comprehension and production that capitalise on the overlap of input and output processing.

## Introduction

Language-emergent models of verbal short-term memory (STM) are premised on transient maintenance of linguistic information arising directly from the architecture of the language system. In such models, short-term "storage" of linguistic information is the by-product of activation of the lexical-semantic and phonological representations in long-term memory that occurs during language comprehension and production (Acheson & MacDonald, 2009; Cowan, 1993; Majerus, 2013; Postle, 2006; Saffran, 1997; Schwering & MacDonald, 2020). If the processes that support verbal STM emerge directly from the language system itself, it follows that verbal STM tasks could be used to investigate the architecture of the language system and yield inferences about language abilities.

Verbal STM deficits tend to co-occur with aphasia and often covary with the individual's relative strengths and weaknesses in semantic and phonological processing (Martin & Ayala, 2004; Minkina et al., 2017; Silkes et al., 2021). Our study probes the relationship between input-only verbal recall span and performance on an output task, picture naming. Outcomes of this investigation will inform theoretical models of the language system's architecture, in particular the relationship between input and output processing pathways, and add to the growing body of evidence for interactive language-emergent models of verbal STM (e.g., Saffran & Acheson, 2011; Martin et al., 1990). Moreover, such detail can potentially inform both the diagnosis and treatment of acquired language disorders such as aphasia by focusing on the mechanisms by which input and output pathways are linked. Diagnostic and therapeutic methods that capitalise on this relationship could be especially useful in cases of severe expressive language or motor-speech impairment (Vieira et al., 2020).

Language-emergent models of verbal STM differ from to multi-component models that temporarily store linguistic representations in specialised buffers. In the Baddeley and Hitch working memory model (Baddeley, 2000; Baddeley & Hitch, 1974), linguistic information is temporarily stored and maintained in a buffer that must be continually refreshed via subvocal rehearsal. It is thought that this covert rehearsal mechanism, known as the *phonological loop*, is composed of both an acoustic store and covert speech articulation (Baddeley & Hitch, 1974). Baddeley's working memory models reliance on acoustic information to store and refresh words successfully explains several phenomena observed in serial repetition tasks (SRT), including the phonological similarity effect (Berndt & Mitchum, 1990; Conrad, 1964, 1965; Conrad & Hull, 1964;

Baddeley, 1966), which refers to poor performance in repetition span tasks containing phonologically related words. The effect has been attributed to interference (Baddeley, 1986) from shared phonemes. Evidence for the influence of phonological information in verbal STM is also supported by the observation that performance drops on SRTs when participants are instructed to repeatedly articulate words aloud during recall tasks (articulatory suppression; Baddeley et al., 1984). While semantic similarity has also been linked to interference in SRTs, the effect is often reported to be much stronger with phonologically similar words (Baddeley, 1966).

Although the importance of phonological information in verbal STM is well established (A.D. Baddeley, 1986; Baddeley et al., 1984; Berndt & Mitchum, 1990; Caplan et al., 1992; Gathercole et al., 1999; Jacquemot & Scott, 2006; Roodenrys et al., 2002), there is considerable evidence for effects of lexical and semantic variables on SRT performance (R. C. Martin et al., 1994; Page & Norris, 1998; Jefferies et al., 2006; Saffran, 1997; R. C. Martin et al., 1999; R. C. Martin & He, 2004; Wheeldon & Monsell, 1992). Words are easier to recall than nonwords (Hulme et al, 1991), as are highly imageable words, believed to have more robust semantic networks (Martin & Ayala, 2004; Martin et al., 1996). Semantic contribution to SRT performance extends beyond the item level. Savill et al. (2018) found that participants are more likely to recall strings that are semantically related, and that semantic relatedness among words to be recalled reduced overall phonological errors.

Models of verbal STM must account for the impact of both phonological and lexical-semantic variables on performance in repetition span tasks. Martin and colleagues extended Dell's Interactive Activation model (Figure 1) (IA model; Dell, 1986; Dell & OSeaghdha, 1992; Dell et al., 1997) to repetition of word sequences (Martin et al., 1996; Martin & Saffran, 1997; Martin & Gupta, 2004), which necessarily engages STM.

According to the IA model, language reverberates through three distinct processing layers: phonological, lexical, and semantic. Levels of representation are accessed sequentially via spreading interactive activation, in both input and output processing of words. The trajectory of spreading activation runs from phonological to lexical to semantic levels for input processing of words and in reverse for output processing of words. In the first step of naming, activation from semantic nodes spreads through the lexical and phonological layers. Feedforward and feedback of activation occurs between

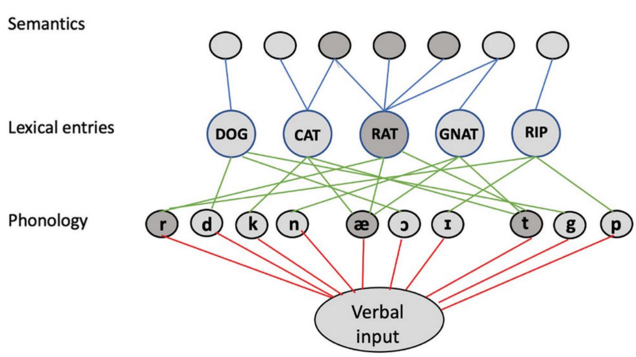


**Figure 1.** The Interactive Activation Model.

layers, priming both the target and competitors until the most activated lexical entry is selected for production. The second step relies on a jolt of activation from the lexicon back to the phonological network for phonological encoding of the selected word. In repetition, the process proceeds in reverse, with phonological-lexical activation occurring first and lexical-semantic second. Martin and Gupta (2004) applied this model toward understanding item-specific recall in serial position tasks. The central finding is that decrements in recall of initial items (i.e., primacy) are associated with semantic deficits, whereas decrements in recall for final (i.e., recency) items are more strongly linked with phonological deficits. This account of serial position effects in aphasia is consistent with language-emergent models of verbal STM (e.g., Martin & Saffran, 1997). These patterns of serial position effects have been verified in individual words, word pairs, triplets, and sentence repetition (Martin & Ayala, 2004; Saffran, 1997; Saffran & Martin, 1990; Sayers et al., 2021).

It is important to note that this model only accounts for the contribution of linguistic representations in long-term memory to short-term maintenance of verbal information. While we contend that the language system is a significant driver of verbal STM, we also acknowledge several additional factors, which modulate verbal STM, including executive function (e.g., Obermeyer et al., 2020; Pompon et al., 2015), and conscious metalinguistic activity, such as subvocal rehearsal (A.D. Baddeley, 1986; Caplan & Waters, 1995). Our focus here is on the contributions of the language system to verbal STM.

Relating input and output processes

Questions regarding the relationship between input and output processing are of immediate clinical relevance in the diagnosis and treatment of language disorders. In children, tasks targeting production can generalize to receptive tasks, suggesting that receptive language processes may be refined through production paradigms (Camarata et al., 2009). In aphasia, success in new word learning is predictive of better outcomes in anomia treatment (Coran et al., 2020; Dignam et al., 2016). It is unclear, however, whether this relationship can be attributed to interactions between input and output language processing or evidence of a shared neurological substrate (. C. Martin et al., 1999; Howard & Nickels, 2005; Martin & Saffran, 2002; Romani et al., 2011).

Models of the architecture of the language system vary in their description of the relationship between input and output processing, ranging from modular systems (R. C. Martin et al., 1999; Howard & Nickels, 2005), to models with partial overlap (Martin & Saffran, 2002; Nickels et al., 1997). Most contemporary models converge upon a unified system of semantic representations, which is used for both input and output processing (Dell et al., 1997; Levelt et al., 1999; Pickering & Garrod, 2004; R.C. Martin et al., 1994). Martin and Saffran (2002) proposed three possible configurations of phonological processing in the context of the IA model: a) a single phonological network, b) separate but coupled input and output phonological networks, and c) separate and independent phonological networks.

Determining fit between cognitive models and behaviour would require devising an input task that is functionally equivalent to a paired output task. True functional equivalence has proven elusive. One alternative approach is to compare performance on an input task that requires a specified phonological skill (e.g., rhyme judgment or auditory lexical decision) with proportion of phonological errors in output (Dell et al., 1997; Martin & Saffran, 2002; R.C. Martin et al., 1994). This approach has yielded inconsistent results, at times favouring separate or coupled input-output phonology (e.g., Martin & Saffran, 2002; Gvion & Friedmann, 2012; R. C. Martin et al., 1999; Monsell, 1984, 1984). This inconsistency across studies may be due to the choices of measures of input and output processing.

Verbal STM tasks can be used to assess different pathways within the language system. Serial repetition tasks engage both input and output lexical-phonological and lexical-semantic pathways. In contrast, probe spans engage only input lexical-phonological and lexical-semantic pathways. A participant is presented with a list of words followed by a probe word and asked to judge if the probe word has the target relationship with *any* of the words in the preceding list and responds with a yes or no. This task has two key benefits. First, it allows for nonverbal responses through a button press indicating yes or no, decoupling measurement of input and output processing, and permitting accurate measurement of verbal STM abilities in individuals with severe expressive language or motor speech impairments. Second, probe spans permit the experimenter to manipulate the nature of the relationship between the words in the string and the probe word to assess the integrity of access to either phonological representations of words (e.g., rhyme, initial CV) or semantic representations (e.g., synonymy or category coordinate). This enables the use of the correlational methods that have been used in previous studies (e.g., Martin & Saffran, 2002; Nickels & Howard, 1995) to investigate the relationship between input and output phonology.

## The present study

The purpose of this study was to investigate the relationship between input and output language processing in the context of language and verbal STM impairment in aphasia. If input and output language processes are not independent, there should be associations between measures of these abilities. Our model is premised on the hypothesis that verbal STM supports both input and output verbal processes. This leads to the prediction that measures of input semantic and phonological STM abilities will correlate with measures of accuracy and error patterns in word production. Our input measures were probe memory spans that were designed to be sensitive to access of semantic or phonological representations. Output measures were naming accuracy and distribution of error types on the TALSA Naming Test (TNT; Martin et al., 2018) that were calculated in both immediate and delayed confrontation naming tasks. We predicted the following:

- Performance on input-only probe span tasks would correlate positively with naming accuracy
- The strength of the correlation should be more pronounced in delayed naming conditions that require stronger engagement of verbal STM processes.

Moving beyond measures of accuracy, the hypothesised relationship between input and output processes also predicts associations between performance on semantic and phonological probe spans and occurrence of specific error types in picture naming. We predicted specifically that:

- Higher semantic span scores would correlate with fewer lexical and semantic errors.
- Higher phonological spans would correlate with fewer phonological errors.

**Table 1.** Demographics.

| Participant | Age | Education | Years post-onset | WAB-R AQ | Aphasia subtype |
|---|---|---|---|---|---|
| KC3 | 55.5 | 14 | 13.9 | 77.4 | TSA |
| EH4 | 51.6 | 13 | 10.8 | 81.4 | anomic |
| CM5 | 53.9 | 10 | 7.3 | 90.3 | anomic |
| EC25 | 68.2 | 18 | 28.5 | 62.6 | Broca's |
| HI28 | 61.1 | 13 | 10.5 | 77.5 | anomic |
| UP35 | 52.6 | 14 | 8.1 | 89.6 | anomic |
| KM38 | 71.0 | 18 | 19.8 | 72.3 | TMA |
| XH46 | 47.9 | 7 | 1.3 | 73.1 | conduction |
| KG47 | 60.8 | 13 | 13.7 | 94.5 | anomic |
| UM48 | 56.7 | 12 | 4.4 | 89.2 | Anomic |
| KT53 | 67.1 | 14 | 3.3 | 48.8 | Wernicke's |
| NF54 | 56.4 | 14 | 3.3 | 89.1 | anomic |
| KK55 | 61.2 | 17 | 10.5 | 78.7 | anomic |
| MN56 | 60.8 | 14 | 10.1 | 81.1 | anomic |
| BQ58 | 39.2 | 16 | 6.3 | 74.8 | conduction |
| ET59 | 69.5 | 14 | 1.7 | 92.4 | anomic |
| BC60 | 67.2 | 16 | 1.4 | 71.4 | Broca's/TMA |
| CI63 | 64.9 | 18 | 10.9 | 61.4 | conduction |
| DS68 | 60.2 | 12 | 1.7 | 82.7 | anomic |
| ZK87 | 58.2 | 14 | 1.2 | 91.1 | anomic |
| *M* | 59.20 | 14.05 | 8.43 | 78.97 | |

*TSA = transcortical sensory aphasia; TMA = Transcortical motor aphasia*

These hypotheses rest on the assumption that higher verbal STM scores are representative of the ability to activate and maintain sufficient activation of lexical-semantic and phonological representations to support performance in word processing tasks. Our results support this hypothesis, which we will report here and review in the General Discussion.

## Method

### *Participants*

This study used a quasi-experimental design with retrospective data from 20 adults with chronic aphasia (8 females). Ages ranged from 32 to 70 years (M = 51.9, SD = 10.4). All participants had a history of single left-hemisphere cerebrovascular accident (Table 1). All were at least 8 months post onset at the time of the assessment. Nineteen participants met the diagnostic criterion for aphasia on the *Western Aphasia Battery-Revised* (WAB-R), which is an aphasia quotient (AQ) less than 93.8 (Kertesz, 2007). All participants were native English speakers with histories negative for neurodegenerative diseases, traumatic brain injury, or learning disability. A single participant was left handed. See, Table 1 for additional details.

This study was approved by the Temple University Institutional Review Board. All participants voluntarily enrolled in the study and signed an approved informed consent form. Testing was completed in the Eleanor M. Saffran Center for Cognitive Neuroscience at Temple University by trained research assistants.

Stimuli

The data for this study came from seven subtests of the Temple Assessment of Language and Short-term memory in Aphasia (TALSA; Martin et al., 2018). The TALSA is a comprehensive test with 21 subtests designed to assess language and verbal STM abilities in people with aphasia. Tasks within the battery provide information on phonological and semantic short-term memory abilities, variation in performance following delay conditions, and various verbal span tasks with both verbal and nonverbal responses (Martin et al., 2018). For this study, we examined performance on six tests of input verbal STM processing and one test of output processing. These subtests are described below.

### *TALSA naming test (TNT)*

Naming performance was assessed using the TALSA Naming Test (TNT). The TNT is a 90-item confrontation naming test that is administered in both 1-second and 5-second response delay conditions. Variance in performance between 1- and 5-second delay conditions provides information on participants' abilities to transmit activation of representations between the levels of processing and maintain activation of representation. Patients with slow transmission of activation generally see an improvement in performance on a task when provided with extra time to respond, while participants with rapid decay (poor maintenance) of activated representations often perform worse in delay conditions (Martin & Dell, 2019).

We also conducted an error analysis using the categorisation system set forth in the PNT (Roach et al., 1996). Lexical errors were coded as *semantic* (belonging to the same superordinate category as the target), *formal* (phonologically similar to the target), mixed (semantically and phonologically similar to the target), and unrelated. Nonlexical errors were coded as phonologically related nonwords similar if they shared the same initial consonant, the same stressed vowel, initial, or final phonemes; two or more phonemes in any position; or one or more phonemes in a corresponding syllable and word position. Nonlexical errors that were not phonologically related were coded as abstruse neologisms but were not included in our analyses since they can arise from multiple disparate pathways. Failures to respond and "I don't know" responses were coded as omissions.

### *Probe spans*

We measured semantic and phonological input verbal STM with six probe span subtests from the TALSA. Probe span tasks use a paradigm introduced by Sternberg (1969;1975) in which participants are presented with a list of words followed by a probe word. Participants must decide if the probe word bears the target relationship with *any* of the members of the preceding list. The target relationship does not change during individual subtests. Participants indicated their response through non-verbal means (i.e., pushing a button), making this an input-only task.

Probe spans are further divided into semantic and phonological spans. Our participants completed three phonological probe spans and three semantic probe spans. Probe–target relationships for phonological probe spans included same initial consonant-vowel pair (hereafter initial CV; field/feet), rhyming (mitten/kitten), and non-word identity. The non-word identity span is a test of non-lexical phonological abilities. In the non-word identity span, participants are presented with a list of nonwords that adhere to the phonotactic rules of English, followed by a probe word. Participants then indicate whether the probe word appeared in the preceding list. Relationships assessed in the three semantic spans administered include same superordinate category (category coordinate span; sweater/pants), same meaning (synonymy span; arrest/detain), and superordinate category relationship (superordinate span; elephant/animals). Self-corrected responses were accepted.

Administration of the probe spans begins with a single item followed by a probe word, increasing to seven items followed by a probe-word. Matches are probed at all positions of an input string and the number of test items increases as the list length increases. For example, List length 1 contains 10 items, list 2 20 items, and so on. If more than 75% of items are answered correctly (i.e., target relationships or lack thereof identified), participants move on to the next list. After a participant fails two consecutive tests by receiving less than 75% accuracy for either "yes" or "no" responses, the administrator discontinues span testing and the participant's span length is calculated. Probe span scores consist of two numbers. The first number is the last list length the participant passed. This is followed by the proportion of the correct strings divided by 0.75 on the first of the two lists; the participant failed. For example, consider a participant who passed list length 3, and completed 66% of items correctly on list 4, and 20% correct on list 5. The first digit of her probe span score would be 3, followed by the proportion of correct strings on list length 4 divided by 0.75 (0.66/0.75). This yields a final span score of 3.88.

## Results

### *Naming and probe span tasks*

Proportional scores on the 90-item TNT in the 1-second and 5-second conditions are shown in Table 2. The two conditions were not significantly different when considered in aggregate ($t$ (19) = −0.59, $p$ = 0.55), but differences in accuracy were present at the individual participant level, some improving in the delayed naming condition and others declining in accuracy. Variability in probe span performance was highly significant for tasks ($F$ (14) = 10.39, $p < 0.000$); see, Table 3). Semantic spans were correlated with each other with correlation coefficients of 0.7 or greater. The initial-CV probe span was highly correlated with all spans ($r > 0.77$) except nonword identity ($r = 0.27$).

### *Correlational analyses*

All probe spans correlated positively with naming accuracy in both the immediate and delayed naming conditions on the TNT (Table 4). The three semantic spans (category-coordinate, superordinate, and synonymy) had moderate positive correlations with naming accuracy in both immediate and delayed naming conditions. Of the phonological probes, initial-CV span, had a significant positive correlation with naming which was significant in both response delay conditions. The rhyme probe and non-word identity probe spans did not reach significance in either condition.

Additional Spearman correlations identified relationships between performance on individual probe span tasks and classes of errors. The three semantic spans (category coordinate, synonymy, and superordinate) along with the initial-CV span had significant, moderate-strength negative correlations with the production of various error classes in both immediate and delayed naming conditions. That is, as probe span performance

**Table 2.** TNT scores and error distributions.

| ID | Score | | Semantic | | Formal | | Mixed | | Unrelated | | Phono. NW | | Omission | | Other* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-sec | 5-sec | 1-sec | 5-sec | 1-sec | 5-sec | 1-sec | 5-sec | 1-sec | 5-sec | 1-sec | 5-sec | 1-sec | 5-sec | 1-sec | 5-sec |
| KC3 | 65 | 71 | 7 | 9 | 1 | 2 | 4 | 4 | 2 | 0 | 8 | 2 | 2 | 1 | 1 | 1 |
| EH4 | 76 | 63 | 3 | 2 | 0 | 1 | 0 | 1 | 0 | 2 | 3 | 3 | 7 | 16 | 1 | 2 |
| CM5 | 88 | 83 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 1 | 0 | 0 | 0 |
| EC25 | 61** | 62** | 2 | 3 | 1 | 0 | 0 | 0 | 1 | 0 | 5 | 3 | 21 | 21 | 0 | 0 |
| HI28 | 65 | 64 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 1 | 13 | 12 | 3 | 8 | 2 | 2 |
| UP35 | 87 | 83 | 3 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 3 | 1 | 6 | 2 | 0 | 1 |
| KM38 | 66 | 55 | 4 | 7 | 0 | 0 | 1 | 1 | 0 | 3 | 6 | 12 | 13 | 6 | 5 | 6 |
| XH46 | 39 | 50 | 5 | 5 | 1 | 2 | 0 | 1 | 3 | 0 | 1 | 7 | 37 | 23 | 4 | 2 |
| KG47 | 78 | 88 | 4 | 0 | 2 | 0 | 1 | 0 | 0 | 2 | 0 | 0 | 4 | 0 | 1 | 0 |
| UM48 | 85 | 83 | 3 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 7 | 2 | 2 | 2 | 0 | 1 |
| KT53 | 28 | 40 | 2 | 2 | 12 | 7 | 2 | 2 | 7 | 5 | 13 | 20 | 21 | 7 | 14 | 7 |
| NF54 | 86 | 80 | 3 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 6 | 0 | 0 | 1 | 1 |
| KK55 | 81 | 75 | 2 | 1 | 1 | 1 | 2 | 1 | 0 | 0 | 1 | 2 | 9 | 7 | 2 | 3 |
| MN56 | 85 | 82 | 1 | 3 | 0 | 2 | 0 | 0 | 1 | 0 | 2 | 1 | 3 | 2 | 1 | 0 |
| BQ58 | 80 | 81** | 4 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 5 | 2 | 2 | 2 | 2 | 3 |
| ET59 | 80 | 86** | 2 | 1 | 1 | 1 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 1 |
| BC60 | 68 | 69 | 3 | 1 | 2 | 1 | 2 | 1 | 0 | 1 | 5 | 2 | 16 | 12 | 1 | 3 |
| CI63 | 45 | 63 | 3 | 4 | 8 | 3 | 0 | 0 | 1 | 0 | 16 | 16 | 13 | 3 | 3 | 1 |
| DS68 | 60 | 54 | 2 | 3 | 2 | 0 | 0 | 0 | 0 | 0 | 5 | 10 | 17 | 17 | 3 | 6 |
| ZK87 | 78* | 81 | 2 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 2 | 5 | 5 | 3 | 1 | 0 |

* abstruse neologisms, perseverations, description, and miscellaneous errors.
**scored on 89 items

**Table 3.** Probe Spans.

| ID | Initial CV | Rhyme | NW Identity | Cat. Coord. | Superordinate | Synonymy |
|---|---|---|---|---|---|---|
| KC3 | 1.93 | 0.53 | 4.91 | 1.53 | 0.53 | 0.27 |
| EH4 | 3.73 | 1.93 | 6.91 | 3.67 | 2.89 | 1.93 |
| CM5 | 2.71 | 1.67 | 6.84 | 2.98 | 2.98 | 2.8 |
| EC25 | 1.93 | 0.8 | 4.96 | 0.27 | 1.27 | 2.89 |
| HI28 | 4.69 | 1.93 | 7.0 | 1.93 | 2.8 | 4.85 |
| UP35 | 3.93 | 1.8 | 5.98 | 2.71 | 2.8 | 1.93 |
| KM38 | 5.93 | 1.8 | 4.8 | 1.93 | 1.67 | 1.93 |
| XH46 | 4.75 | 0.8 | 7.0 | 1.53 | 2.53 | 1.93 |
| KG47 | 7.0 | 4.85 | 5.98 | 7.0 | 5.89 | 7.0 |
| UM48 | 6.91 | 4.85 | 6.76 | 5.8 | 4.96 | 5.89 |
| KT53 | 1.67 | 0.53 | 0.8 | 0.53 | 0.27 | 0.8 |
| NF54 | 0.8 | 1.27 | 6.91 | 1.53 | 1.8 | 3.8 |
| KK55 | 1.93 | 1.93 | 4.96 | 1.27 | 1.8 | 2.89 |
| MN56 | 2.89 | 2.71 | 5.71 | 3.84 | 3.53 | 4.75 |
| BQ58 | 1.8 | 0.8 | 7.0 | 2.97 | 2.88 | 1.8 |
| ET59 | 6.99 | 4.85 | 4.85 | 4.69 | 6.0 | 5.84 |
| BC60 | 1.93 | 2.8 | 7.0 | 0.8 | 3.93 | 1.67 |
| CI63 | 0.8 | 0.53 | 3.67 | 2.44 | 1.67 | 0.8 |
| DS68 | 3.47 | 0.8 | 4.85 | 2.98 | 4.69 | 3.87 |
| ZK87 | 3.73 | 1.8 | 3.93 | 1.8 | 2.89 | 2.53 |

*NW Identity = nonword identity; Cat. Coord. = category coordinate*

**Table 4.** Correlations between naming accuracy and probe span scores.

| | Initial CV | Rhyme | NW Identity | Cat. Coord | Superordinate | Synonymy |
|---|---|---|---|---|---|---|
| TNT – immediate | 0.668* | 0.24 | 0.23 | 0.585* | 0.557* | 0.543* |
| TNT – delayed | 0.611** | 0.33 | 0.17 | 0.61** | 0.609** | 0.491* |

*Note: * $p < 0.05$** $p < 0.01$ NW Identity = Nonword Identity; Cat. Coord = Category Coordinate*

improved, the proportions of various errors declined. There was no clear pattern of error types affected (See, Tables 5). For example, the three semantic spans were negatively correlated with production of unrelated errors in the immediate naming condition (i.e., greater spans correlated with fewer unrelated errors errors) but not in the delayed naming condition. The three semantic spans were instead significantly negatively correlated with the production of mixed errors (i.e., longer spans predict fewer mixed errors) in the delayed naming condition. The initial-CV span was associated with reductions in total lexical and non-lexical errors in both the immediate and delayed naming conditions, however the relationship with non-lexical errors was significant in both conditions (p = .046, .004) and only trended towards significance with lexical error (p = .091, .075). Once again, rhyme and non-word identity spans did not correlate with error classes in immediate and delayed naming conditions.

## *Principal component analysis*

Contrary to our hypothesis, we did not find that greater semantic probe spans were associated with fewer semantic errors. Similarly, greater phonological spans were not associated with fewer phonological errors. Despite the lack of a clear pattern in the individual correlations between spans and error classes, there is some suggestion of a degree of interaction. Multicollinearity within the probe span data precluded their use together as predictive variables in a parametric linear regression. We conducted a

**Table 5.** Correlations for probe spans and naming errors.

| | Semantic | | Formal | | Mixed | | Unrelated | | Phono. NW | | Omission | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-sec | 5-sec | 1-sec | 5-sec | 1-sec | 5-sec | 1-sec | 5-sec | 1-sec | 5-sec | 1-sec | 5-sec |
| Initial CV | −0.20 | −0.64** | −0.28 | −0.19 | 0.13 | −0.24 | −0.66* | 0.19 | −0.42 | −0.61** | −0.34 | −0.23 |
| Nonword Identity | 0.06 | −0.29 | −0.24 | −0.25 | 0.03 | −0.16 | −0.40 | 0.24 | −0.31 | −0.33 | −0.10 | −0.06 |
| Rhyme | 0.20 | −0.30 | −0.39 | −0.04 | −0.32 | −0.08 | −0.27 | 0.00 | −0.23 | −0.22 | −0.22 | 0.06 |
| Category Coordinate | 0.01 | −0.29 | −0.29 | −0.22 | −0.23 | −0.51* | −0.42 | −0.04 | −0.29 | −0.43 | 0.50* | −0.48 |
| Superordinate | −0.16 | −0.56* | −0.13 | −0.36 | −0.10 | −0.48* | −0.53* | −0.10 | −0.58* | −0.55* | −0.36 | −0.27 |
| Synonymy | −0.42 | −0.44 | −0.24 | −0.30 | −0.20 | . −0.61** | −0.53* | −0.17 | −0.456* | −0.35 | −0.37 | −0.24 |

*Phono. NW = phonologically related nonword. ** $p<0.05$

**Table 6.** Latent factor loadings.

| Probe Span | Factor 1 | Factor 2 | Factor 3 |
|---|---|---|---|
| Initial CV | 0.47 | 0.87 | 0.07 |
| Non-word Identity | 0.17 | 0.06 | 0.98 |
| Rhyme | 0.47 | 0.46 | 0.1 |
| Category coordinate | 0.81 | 0.37 | 0.13 |
| Superordinate | 0.84 | 0.31 | 0.25 |
| Synonymy | 0.88 | 0.23 | 0.14 |

principal component analysis (PCA) with varimax rotation to decorrelate the semantic and phonological probe span scores and identify the optimal number of latent factors. PCA transforms and decorrelates variables into factors by applying weightings, producing factors that each account for a percentage of sample variance. In the present analysis, an eigenvalue threshold of 0.8 identified 2 latent factors that accounted for 83.7% of the variance in span scores. Visual evaluation of the Scree test (Cattell, 1966) revealed a levelling of the curve between components three and four that warranted consideration of a third factor.

The three orthogonal latent factors together accounted for 89.6% of sample variance. A threshold of 0.4 was used for factor membership (Table 6, Table 7). Factor one accounted for 69% of the variance in the sample and was heavily weighted for the three semantic spans and the initial CV span. These factor loadings suggest a latent variable that reflects *lexical-semantic activation*. Factor two explained 15% of the total variance and was weighted at .87 for rhyme span, which tracks a skill previously associated with *lexical-phonological* activation (Martin & Saffran, 2002). Initial CV was also weighted just over the threshold and was also included in this factor. The third factor accounted for 5% of the variance in the sample and was weighted above threshold for only NW identity (0.98). We interpreted this factor to be representative of non-lexical phonological skills (hereafter non-lexical phonological factor)

## *Regression analyses 1: latent factors and naming accuracy*

We completed a series of parametric regressions with the three factors as predictive variables and naming accuracy on the TNT as the outcome. In the immediate naming condition, the regression model was significant and accounted for 53% of the variance in TNT accuracy ($R^2$ = .53, F (3,16) = 6.13, p = .0056). Lexical-semantic and lexical-phonological factors were both significant and of relatively equal strength (β = 0.51, 0.52, p-value = .008, .007, respectively). The non-lexical phonological factor did not reach significance (p = .90). A subsequent model did not identify significant interaction effects between the lexical-semantic and lexical-phonological factors (p = .82). The model without interaction effects remained significant in the delayed naming condition and accounted for 49% of sample variance ($R^2$ = .49, F (3,16) = 5.19, p = .01). Only the lexical-semantic factor remained significant, with a standardised beta coefficient of 0.61, p = .003. In the delayed naming condition, the lexical-phonological factor trended towards significance (p = .08), but the non-lexical-

**Table 7.** Regressions analysis with latent factors predicting errors: Immediate naming.

| | Predictive variables | | |
|---|---|---|---|
| Model (DV) | Lexical-Semantic | Lexical-Phonological | Non-lexical Phonological |
| Semantic | −0.18 | 0.14 | 0.10 |
| p = .65 | | | |
| Phono. NW | −0.36** | −0.36** | −0.25 |
| p < .001 | | | |
| Formal | 0.11 | −0.93** | −0.64* |
| p = .09 | | | |
| Unrelated | −1.48* | −0.54** | −0.41 |
| p = .47 | | | |
| Omission | −0.62** | −0.10 | 0.00 |
| p < .001 | | | |
| Total Lexical | −0.26* | −0.4** | −0.03 |
| p = .005 | | | |
| Total Nonlexical | −0.5** | −0.38** | −0.11 |

*Summary of parameter estimates for regression models with latent factors predicting error classes in the delayed naming condition (e.g., Model 1: semantic errors predicted by lexical-semantic, lexical-phonological, and non-lexical phonological factors)*

phonological factor was non-significant ($p = .75$). The predictive strength of the lexical-semantic factor ($\beta = 0.61$) was nearly twice as strong as the lexical-phonological factor ($\beta = 0.33$) in the 5-second delay condition.

### *Regression analyses 2: latent factors and naming error types*

We performed a series of Poisson regressions to identify predictive relationships between the three latent factors and count data of error types in both immediate and delayed naming conditions (see Tables 7 and 8). All significant predictive relationships between the latent factors and error types had negative beta-coefficients in the immediate naming condition. This is to say, as performance in the skills tracked by the three latent factors

**Table 8.** Regression analysis with latent factors predicting errors: Delayed naming.

| | Predictive variables | | |
|---|---|---|---|
| Model (DV) | Lexical-Semantic | Lexical-Phonological | Non-lexical Phonological |
| Semantic | −0.69** | 0.14 | 0.10 |
| p = .41 | | | |
| Phono. NW | −0.48** | −0.33** | −0.10 |
| p < .001 | | | |
| Formal | −0.31 | −0.47** | −0.17 |
| p = .17 | | | |
| Unrelated | −0.20 | −0.68** | 0.61 |
| p = .12 | | | |
| Omission | −0.55** | 0.17 | −0.04 |
| p < .001 | | | |
| Total Lexical | −0.58** | −0.27* | 0.05 |
| p = .19 | | | |
| Total Nonlexical | −0.5** | −0.38** | −0.11 |
| p < .001 | | | |

*Summary of parameter estimates for regression models with latent factors predicting error classes in the delayed naming condition (e.g., Model 1: semantic errors predicted by lexical-semantic, lexical-phonological, and non-lexical phonological factors)* increased, the likelihood of these error classes decreased. Most predictive relationships in the delay condition followed this pattern, apart from a predicted increase in the odds of unrelated errors as nonlexical phonological skills improved in the delay condition.

The lexical-semantic factor predicted fewer phonologically related non-word errors, unrelated errors, and omissions in the immediate naming condition, and fewer semantic errors, phonologically related nonwords, and omissions in the delayed condition. Lexical-phonological abilities were associated with fewer phonologically related non-words, formal errors, and unrelated errors in both naming conditions. Non-lexical phonological abilities predicted fewer formal errors in the immediate naming condition and reductions in phonologically related nonwords in the delayed condition.

For several error types, the effects of lexical-semantic abilities on reduction of some classes of errors were more pronounced in the delayed naming condition, however this finding was not consistent. No factors were identified as significant predictors of semantic errors in the immediate naming condition. The lexical-semantic factor had a negative predictive relationship with semantic errors in the delayed naming condition, estimating a 38% decrease in the odds of producing semantic errors for each unit increase in the lexical-semantic factor ($p = .0009$). Increased lexical-semantic skills predicted a relatively stable reduction in the rate of phonologically related nonwords and omissions in both conditions. Its predictive relationship with unrelated errors was strong in the immediate naming condition ($B = -1.48$) but did not reach significance in the delay condition. Lexical-semantic and non-word phonological factors were both significant predictors of decreases in total non-lexical errors, while the lexical-phonological contribution gained strength in the delay condition.

The only instance of a positive predictive relationship between latent factors and error classes involved unrelated errors in the delay condition. A one unit increase in the non-lexical-phonological factor predicted 84% greater odds of unrelated errors ($B = 0.61$, $p = .02$). Similarly, a one unit increase in the lexical-phonological factor predicted 19% greater odds of omissions.

## Discussion

The present study investigated the relationship between input-only verbal STM tasks and picture naming in a sample of participants with chronic aphasia. Our data provide three clinically and theoretically relevant findings: a) performance on input-only semantic and the initial CV probe span tasks was positively correlated with naming accuracy; b) measures of input semantic and phonological STM abilities were negatively correlated with occurrences of their corresponding naming error types (i.e., as input verbal STM span increased, fewer errors occurred), and c) latent factors in the probe span data predicted distributions of naming errors consistent with stages of word production in an IA model, lexical-semantic, lexical phonological, and non-lexical phonological. In addition, our results support models that stipulate serial access to phonology (e.g., Wilshire & Saffran, 2005) in which the initial consonant-vowel pair is associated with lexical-semantics and the rhyme is associated with lexical-phonology. Contrary to our hypothesis, we did not consistently find that the strength of a predictive relationship between a probe span and naming accuracy was stronger in the delayed naming condition. Latent factors identified within the probe span data demonstrated predictive relationships with specific error

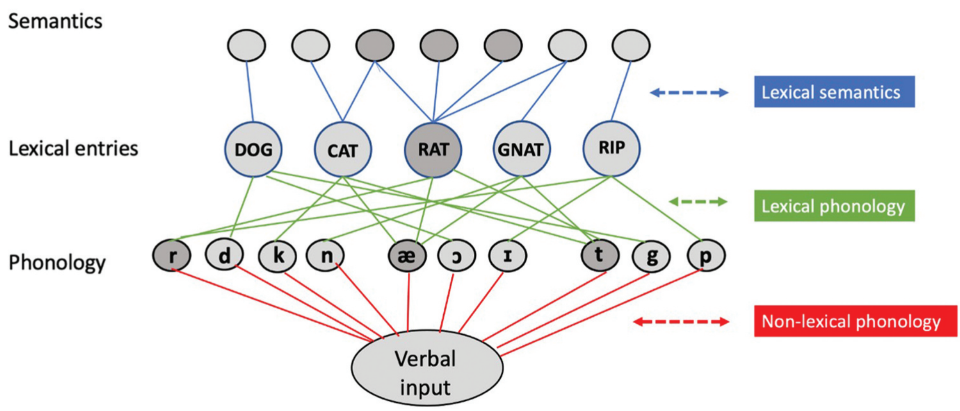


**Figure 2.** Latent factors and the Interactive Activation Model.

types depending on the naming response delay condition. For example, higher scores on the initial CV span predicted fewer semantic errors in the delayed condition, but not the immediate naming condition.

The heavily weighted spans in each of the latent factors align with processes described in the IA model (Figure 2). In the IA model, transmission of lexical-semantic activation is the first and most prominent driver of naming accuracy. Lexical nodes that are primed by feedforward activation spread activation forward to phonological nodes (lexical-semantic factor). The lexical nodes begin to decay immediately, but they are re-activated by phonological feedback (lexical-phonological factor). This has the effect of stabilising the activation of the target lexical node and other semantically related words primed by semantic-lexical activation.

Semantic probe spans and the initial CV span were strongly and positively correlated with naming accuracy in both immediate- and delayed-naming conditions. Although the two other phonological probe spans did not reach significance in correlations with naming accuracy or error types, they were associated with latent factors (lexical phonological and non-lexical phonological) which together accounted for a significant portion of variance within the sample.

Probe spans and the IA Model

The three latent factors in the probe span data align with patterns of interaction in Dell's IA model (Dell et al., 1997). The lexical-semantic factor was heavily weighted for probe spans associated with the initial feedforward of semantic activation. The role of interactive feedback between the lexicon and phonology in naming accuracy was captured in the lexical-phonological factor. Feedback from phonology reinforces the activation of lexical forms that already occupy higher activation levels due to the initial burst of lexical-semantic activation. Non-lexical phonology, the third factor, explained the smallest proportion of sample variance. This factor may capture non-lexical phonological skills like those represented in models of echoic memory (Craik & Lockhart, 1972) or the non-lexical input route for repetition as described in Nozari and Dell (2013).

Predictive relationships between latent factors and error distributions were also in line with expectations based on timescale of interaction within the IA model. The lexical-semantic factor predicted a reduction of unrelated errors in the immediate naming condition. Following a five-second delay, only lexical-phonological feedback predicted fewer unrelated errors. An account of this pattern within the IA model could be that robust and enduring lexical-semantic activation can minimise the competition of unrelated lexical competitors in the first step. Adequate lexical-phonological feedback in the second step is then required to avoid erroneous selection of unrelated lexical targets (Table 8 and Figure 2). The IA model attributes unrelated errors to "noise" from residually activated lexical entries from prior attempts at naming or distantly related targets combined with rapid lexical-semantic decay (Dell et al., 1997). On this account, the likelihood of unrelated errors should increase over time. It appears that the influence of semantic ability on a reduction of unrelated errors diminishes over time. This may suggest increased influence of both lexical and non-lexical phonological feedback on unrelated lexical errors following a delay. Similar stabilising effects of lexical- and non-lexical phonological abilities on targets primed by the initial burst of lexical-semantic activation were seen in the reduction of formal errors in both immediate and delayed naming conditions.

The lexical-phonological factor was associated with a reduction in formal errors in both the immediate and delayed naming conditions. The non-lexical phonological factor was significant in the immediate condition, and the lexical-semantic factor did not reach significance in either condition. The Dell model describes two pathways to formal errors (Dell et al., 1997). Formal errors can occur during lexical selection when words that share phonemes with the target word become activated during feedback, such that *mat* could be selected instead of *cat* due to overlap in the rhyme (/æt/) and residual activation of the onset (/m/). Alternately, formal errors could arise after lexical selection if incorrect phonemes residually activated or strengthened by noise outcompete members of the target and happen to result in a word error by chance. Occurrences of formal errors arising from either pathway would be reduced in individuals with intact ability to maintain activation of lexical-phonological information.

Stronger lexical-semantic and lexical-phonological factors were associated with reduced phonologically related nonword errors. Phonologically related nonword errors have two sources in this model either errors in the selection of phonemes primed by other activated lexical entries or errors during the phonological encoding stage (Dell et al., 1997). Only the lexical-semantic factor was associated with fewer omissions. Lexical selection proceeds in a stepwise fashion in which lexical-semantic activation occurs first. Lexical-phonological activation and non-lexical phonological knowledge cannot be increased to sufficiently offset failures in lexical-semantic transmission of activation. If lexical-semantic transmission is weak, there will be little or no activation of phonological nodes, and consequently weak or absent phonological activation.

## *Probe spans and sequential access to phonology*

Although the three phonological probe spans were initially intended as measures of phonological processing (Martin et al., 2018), the data aggregated in such a way to associate them with separate steps in lexical selection and output processing. The lexical-semantic factor included all three semantic spans plus the initial-CV span, but the lexical-phonological factor was most heavily weighted in the rhyme span.

In aphasia, the effects of phonological priming and phonological cues yield different results depending on the nature of language processing deficit in the patient. The inclusion of the initial-CV span in the lexical-semantic factor reflects the relationship between the initial sounds in a word with the lexical-semantic step of word retrieval (Wilshire & Saffran, 2005; Gordon & Baum, 1994; Goodglass et al., 1997). Gordon and Baum (1994) reported that initial CV primes reduced reaction times in a lexical decision task for participants with lexical-semantic deficits. Similarly, Wilshire and Saffran (2005) found that initial CV primes facilitated increased naming accuracy in a participant with semantic deficits, while rhyme-related primes facilitated naming accuracy in a participant with phonological deficits. Additional complexities regarding how phonological cues facilitate naming may include details regarding syntactic category (Lee & Thompson, 2015) and visual features of the target to be named (Meteyard & Bose, 2018).

Our data support the notion that access to the lexicon occurs sequentially from initial to final phonemes, with the initial-CV occupying a pivotal role in access to the lexicon. In the IA model, activation spreads from lexical representations to their phonological components, which are coded for location within the syllable (i.e., onset, rhyme, coda; Dell & OSeaghdha, 1992). This activation occurs *simultaneously* for all positions within the word. Differences between models with serial versus simultaneous access to phonology lead to different predictions regarding the effect of phonological priming and distributions of errors in the output of individuals with disordered language systems (Martin & Saffran, 2002). With serial access to phonology, initial CV primes would facilitate access to the lexicon via feedback from phonological activation of the phonemes. Rhyme-related primes are associated with the second stage of lexical retrieval (Wilshire & Saffran, 2005) and would help to stabilise phonological activation of lexical representations previously activated in the first stage.

### *Practical applications*

The link between input verbal STM abilities and output processing is of both clinical and theoretical relevance. This association motivates development of diagnostic tools that use analysis of input verbal STM to infer the integrity of semantic and phonological processing and its impact on verbal comprehension and production. Diagnostic tools of this nature would be particularly useful with patients with severe expressive deficits. sparse or repetitive output, or concomitant motor speech disorders. Recent investigations demonstrate that the inclusion of verbal STM measures, such as input-only tasks and delay conditions, can yield detailed deficit profiles on patients with severe expressive output processing deficits who experience floor effects in standardised assessments (Vieira et al., 2020). The TALSA category coordinate span was also identified as a measure of verbal STM that discriminated between patients with latent aphasia and controls (Silkes et al., 2021). Therapies currently under investigation to improve semantic STM are functionally relevant in that they support enduring lexical-semantic activation. While these findings do not speak to the nature of the relationship, they do support that input-only processing measures can permit clinicians to identify the relative integrity of semantic and phonological processing. The overlap between input and output processing may also be of therapeutic use in aphasia rehabilitation. It may be possible to capitalise on input-only activation and maintenance of representations for the purposes of output rehabilitation. This further emphasises the value of addressing both input and output language processes in all patients.

The lexical-semantic and lexical-phonological factors provided roughly equal contributions to naming accuracy in the immediate naming condition, but in the delayed naming condition, the lexical-phonological factor's effect was half as strong. Phonological activation has been shown to be more durable when bound to semantic information (Savill et al., 2018). This is relevant to the selection of stimuli for treatment activities. Individuals with poor access to semantics but retained lexical-phonological skills (e.g., transcortical sensory aphasia) may require additional semantic support in delay conditions (e.g., high imageability words, semantically related contexts) in delay conditions.

From a theoretical standpoint, our data support models in which input semantic processing overlaps with output. Our participants' input semantic abilities were positively correlated with naming accuracy and latent factors in their probe span scores were negatively correlated with various error types.

### *Limitations*

This study has several limitations, most arising from our use of retrospective data in a post hoc quasi experimental design. Our sample contained participants with varying degrees of severity and deficit profiles. Future studies should seek larger samples or focus on subsets of the aphasia population, such as nonfluent aphasia or a preselected severity level. We also did not use a control group in this analysis. While control data were available, they could not be used due to a sampling error. There is always some degree of subjectivity in interpretation of principal components analysis, however the proportions and strength of relationships identified in latent factors despite the small sample and their respective members are well supported under the IA model.

## Conclusions

In language-emergent models, verbal STM is supported by activation of lexical-semantic and phonological representations in long-term memory. Our study extends Vieira et al.'s (2020) recent findings that input-only tasks can be used to assess retained linguistic competencies in people with aphasia, demonstrating that these tasks can also be used to predict naming performance and error distributions in a sample of patients with a range of severity. Our results also suggest some degree of overlap in input and output phonological processing. This has implications for the architecture of the lexical processing system and application to clinical methods of diagnosis and treatment. Future studies should systematically test input and output processes to identify relationships that can be leveraged for diagnostics and seek to identify treatments that engage both input and output processes simultaneously.

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