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Newly-acquired words are more phonologically robust in verbal short-term memory when they have associated semantic representations

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ABSTRACT

Verbal short-term memory (STM) is a crucial cognitive function central to language learning, comprehension and reasoning, yet the processes that underlie this capacity are not fully understood. In particular, although STM primarily draws on a phonological code, interactions between long-term phonological and semantic representations might help to stabilise the phonological trace for words ("semantic binding hypothesis"). This idea was first proposed to explain the frequent phoneme recombination errors made by patients with semantic dementia when recalling words that are no longer fully understood. However, converging evidence in support of semantic binding is scant: it is unusual for studies of healthy participants to examine serial recall at the phoneme level and also it is difficult to separate the contribution of phonological-lexical knowledge from effects of word meaning. We used a new method to disentangle these influences in healthy individuals by training new 'words' with or without associated semantic information. We examined phonological coherence in immediate serial recall (ISR), both immediately and the day after training. Trained items were more likely to be recalled than novel nonwords, confirming the importance of phonological-lexical knowledge, and items with semantic associations were also produced more accurately than those with no meaning, at both time points. For semantically-trained items, there were fewer phoneme ordering and identity errors, and consequently more complete target items were produced in both correct and incorrect list positions. These data show that lexical-semantic knowledge improves the robustness of verbal STM at the sub-item level, even when the effect of phonological familiarity is taken into account.

1. Introduction

Communication, thought and vocabulary acquisition draw on verbal short-term memory (STM) – i.e., the ability to actively maintain verbal information for brief periods. Theoretical accounts of this function have suggested it largely reflects temporary activation of a phonological code (Baddeley and Hitch, 1974; Baddeley, 1986, 2000). However, STM plays a crucial role in extracting and conveying semantic information through language. Semantic representations might, therefore, influence the stability of the phonological trace and this effect might be crucial for understanding word learning and comprehension at a sub-item level.

We know that speech sounds are maintained better in STM when they are meaningful. When participants reproduce a sequence of items in order, as in immediate serial recall (ISR), performance is better for lists of words that are higher in imageability/concreteness (Acheson et al., 2010; Allen and Hulme, 2006; Caza and Belleville, 1999; Hoffman et al., 2009; Jefferies et al., 2006a; Majerus and van der Linden, 2003; Roche et al., 2011; Romani et al., 2008; Walker and Hulme, 1999; Wilshire et al., 2010), related in meaning (Poirier and Saint-Aubin, 1995; Saint-Aubin et al., 2014; Wilshire et al., 2010), or when word meaning has been emphasised at encoding (Campoy and Baddeley, 2008; Savill et al., 2015b).

Furthermore, patients with semantic dementia – who show progressive loss of semantic knowledge associated with atrophy of the anterior temporal lobe – have difficulty maintaining the correct phonological forms of words that are poorly understood (Hoffman et al., 2009; Jefferies et al., 2006, 2004; Knott et al., 1997; Majerus et al., 2007; Patterson et al., 1994). As first noticed by Patterson et al. (1994), these patients frequently recombine the phonological elements of different items in ISR, particularly when repeating words with more degraded meanings, despite fluent speech production and generally intact phonological performance. ISR impairments related to compromised semantic function have since been observed in patients with Alzheimer's disease (Peters et al., 2009) and those with focal frontal and temporal lesions

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(Forde and Humphreys, 2002; Jefferies et al., 2008; Wilshire et al., 2010).

Nevertheless, there is disagreement regarding the way in which semantic information influences verbal STM; whether beneficial effects of word meaning occur at a lexical level or sub-lexical phoneme level. Some accounts have proposed that semantic information might aid STM via a process of 'redintegration', whereby the phonological trace that has degraded over time is actively reconstructed from long-term lexical knowledge – for example, semantic information would enable participants to establish if they had been presented with the word 'man' or 'map', allowing the complete item to be produced accurately, but not necessarily in the correct location within the list (Poirier and Saint-Aubin, 1995; Walker and Hulme, 1999). Alternatively, 'linguistic' accounts have proposed that semantic information influences the stability of the phonological trace more directly, by virtue of bidirectional connections between these systems (Acheson and MacDonald, 2009; Jefferies et al., 2009; Patterson et al., 1994). That is, in both speech production and auditory comprehension tasks, activation in the phonological system is thought to represent a sequence of phonemes in order, and this phonological processing co-occurs with semantic activation. As a consequence, semantic activation might benefit serial order memory in the phonological system. Most models of language processing allow interactive-activation between semantics and phonology (e.g., Dell et al., 1997; Patterson et al., 1994; Plaut and Kello, 1999; Plaut et al., 1996) – although these models rarely include an explicit phoneme sequencing mechanism. Nevertheless, the finding of better ISR for more meaningful verbal information can potentially emerge naturally from accounts of STM that explain this capacity in terms of temporary activation or weight changes within the language system (see Majerus, 2013, for an overview).

If we assume that the phonological system has an in-built capacity to maintain a string of speech sounds in order, we might envisage that semantic information can constrain the order of phonemes in verbal STM. The "semantic binding hypothesis" proposed by Patterson et al. (1994) suggests that the phonemes of words can be maintained in the correct configuration more easily than phonemes corresponding to nonwords for two reasons: (i) the phonological system learns familiar sequences and thus develops "pattern completion properties" for words; (ii) the phonological system receives further stabilising input from co-activation with semantic representations, strengthening this pattern completion effect for words.[1] This theoretical framework predicts that semantic information contributes to order memory but specifically at the level of individual phonemes – i.e., the constituents of words should be *less likely* to split apart, to migrate to a different place in the sequence and be recombined with the elements of other list items. Importantly, this account differs from the current redintegration perspective in its assumption that the position of phonemes in STM is inherently unstable and vulnerable to migration or loss, and it is the availability of long-term representations that help to bind phonemes together and reduce such movement. Recall-based accounts (such as redintegration) assume the quality/stability of the available phonological trace in STM itself is not directly influenced by long-term activation –and, as such, do not include a mechanism to predict patterns in sub-item phoneme movement. At the whole-item level, in contrast, both the redintegration and semantic binding hypotheses predict a potential *increase* in order errors with greater semantic support, since strong binding (or redintegration of an item) should encourage all of the elements of a word to be recalled together, even when the location of the item in the list is incorrect.

The predictions arising from the semantic binding hypothesis have important implications for our understanding of word learning and comprehension but these predictions have not been adequately tested because (i) most studies of immediate serial recall have examined performance at the level of whole items and have not looked for a semantic influence on order memory at the phoneme level and (ii) it is difficult to examine the influence of semantic information on phonological maintenance independently of phonological-lexical familiarity. Studies that have examined phoneme-level recall have largely failed to separate these factors. The semantic binding hypothesis was originally proposed to explain the tendency of patients with semantic dementia to recombine phonemes across different items in immediate serial recall for semantically-degraded words (Hoffman et al., 2009; Jefferies et al., 2004; Knott et al., 1997; Majerus et al., 2007; Patterson et al., 1994). This phoneme error pattern is also seen for nonwords compared to words in healthy individuals (Hoffman et al., 2009; Jefferies et al., 2006a, 2006b, 2009). However, semantic binding might not be necessary to explain this ISR advantage for 'known' words relative to semantically degraded items or nonwords, since familiarity with the phonological form of words alone, without an accompanying semantic representation, also benefits phonological stability (Benetello et al., 2015; Savill et al., 2015a). We recently showed that familiarisation with the phonological form of nonwords *without* meaning increased the coherence of these items in ISR (Savill et al., 2015a). Thus, it has been proposed that differences in phoneme migrations for 'known' and 'semantically degraded' words in semantic dementia might relate to greater phonological familiarity and frequency of usage for words that are still understood (Papagno et al., 2013).

One way to determine if semantic information benefits short-term phonological maintenance independently of phonological-lexical familiarity is to test ISR for trained sets of items matched for exposure to the phonological-lexical form, but varying in the availability of semantic support. This broadly constituted the approach in a recent study that found no difference in ISR between foreign words familiarised with and without semantics (Benetello et al., 2015), leading the authors to conclude that, in the context of supporting recently familiarised phonological-lexical forms in STM, 'meaning is useless'. However, the study's design might have restricted sensitivity to semantic effects, since there was a small set of items for each condition (N = 10) and each condition was tested separately; thus the ISR test was characterised by massed repetition. Lexical and semantic effects on ISR are strongest in open sets of non-repeated items (Jefferies et al., 2004; Roodenrys and Quinlan, 2000): small, closed sets maximise demands on whole-item order memory, while the use of more open sets taps the retention of phoneme order and item identity, which are most likely to benefit from semantic support. In addition, Benetello et al. tested ISR immediately after training yet previous research suggests that lexical and semantic learning effects may emerge or strengthen after a period of consolidation. For example, Davis and Gaskell's complementary systems account of word learning characterises a process of 'lexicalisation' over time, particularly after a period of sleep (Davis and Gaskell, 2009; see also McClelland et al., 1995). Evidence for the acquisition and integration of semantic representations for new words also emerges after sleep (e.g., Clay et al., 2007; Lin and Yang, 2014; Tamminen and Gaskell, 2013).

1.1. The present study

To examine whether semantic information increases the stability of the phonological trace, independently of phonological familiarity, we considered 1) if nonwords trained with a semantic

[1] Patterson et al.'s (1994) hypothesis discusses the influence of long-term representations on STM in terms of the strength of ongoing temporary activation, but more recent work suggests that STM can occur via synaptic priming (Lewis-Peacock et al., 2012), which would yield similar predictions.