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Slave to the rhythm: Experimental tests of a model for verbal short-term memory and long-term sequence learning

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ABSTRACT

Three experiments tested predictions of a neural network model of phonological short-term memory that assumes separate representations for order and item information, order being coded via a context-timing signal [Burgess, N., & Hitch, G. J. (1999). Memory for serial order: A network model of the phonological loop and its timing. *Psychological Review, 106,* 551–581005D]. Predictions were generated for long-term sequence learning and tested using the Hebb Effect, the improvement in immediate serial recall when a list is repeated. Results confirmed predictions that the Hebb Effect would be (1) insensitive to phonemic similarity and articulatory suppression, variables that impair immediate recall without affecting the context-timing signal and (2) reduced if the context-timing signal is altered by varying the temporal grouping pattern of the repeated list. Results highlighted an interesting shortcoming of the model in that participants were able to learn more than one sequence simultaneously. However, this problem was addressed by extending the model to include multiple context representations and a sequence-recognition process.

Introduction

According to the model of working memory proposed by Baddeley and Hitch (1974) short-term memory (STM) for a sequence of verbal items depends on a speech-based storage system known as the phonological loop (see also Baddeley, 1986, 2007). A wide range of empirical evidence suggests that an important function of this store is to support vocabulary acquisition (Baddeley, Gathercole, & Papagno, 1998), the idea being that a new word form must be held in short-term phonological storage in order for long-term learning to take place. However, the theoretical concept of the phonological loop requires elaboration if it is to offer an explanation of how such long-term learning takes place. This is primarily because it does not address the twin problems of how order information is represented in STM and how STM and long-term memory (LTM) interact. Burgess and Hitch (1999) described an implementation of the phonological loop as a neural network that included explicit mechanisms for both serial order and long-term learning. This was a development of an earlier neural network model that addressed serial order but not long-term learning (Burgess & Hitch, 1992). In the present article we report experiments that test qualitative predictions of the Burgess and Hitch (1999) model for sequence learning. The results broadly confirm the predictions but draw attention to the need to revise the model so as to be capable of learning multiple sequences without massive interference.

We begin by briefly describing the concept of the phonological loop. We then explain how the network model of Burgess and Hitch (1999) addresses serial order and long-term learning and show how the model can be used to predict the sensitivity of sequence learning to variables known to influence short-term recall. These predictions depend critically on whether the variable affects item or order information. We then introduce an experimental

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procedure due to Hebb (1961) as a suitable vehicle for testing these predictions.

Phonological loop

As initially proposed, the phonological loop consists of two components: a phonological store that decays over time and a subvocal rehearsal mechanism capable of refreshing the contents of the store (Baddeley, 1986). This simplistic conceptual model was used to explain the effects of a cluster of related variables on verbal STM and their interactions, principally word length (Baddeley, Thomson, & Buchanan, 1975), phonemic similarity (Baddeley, 1966; Conrad & Hull, 1964) and articulatory suppression (Murray, 1967). The tendency for lists of long words to be harder to recall than short words was attributed to the extra time taken to rehearse long words and refresh their decaying memory traces. The tendency for lists of similar-sounding items to be less well recalled than dissimilar items was explained by the extra difficulty of discriminating partially decayed traces of similar items in the phonological store. Articulatory suppression involves repeating an irrelevant utterance and is used as a secondary task to disrupt subvocal rehearsal (Murray, 1967). Suppression impairs immediate serial recall and removes the word length and phonemic similarity effects (Baddeley et al., 1975; Murray, 1968; Peterson & Johnson, 1971), consistent with it disrupting the phonological loop. The precise pattern of interactions depends on presentation modality. Thus, suppression removes the word length effect for visual and auditory lists but removes the phonemic similarity effect only for visual lists (Baddeley, Lewis, & Vallar, 1984). This effect of presentation modality was explained by a modest elaboration of the model, such that auditory items access the phonological store automatically whereas visual items have first to be verbally recoded, suppression being assumed to block the recoding process in addition to preventing subvocal rehearsal.

The concept of the phonological loop has proved influential and has been successfully applied in areas beyond its initial remit, including child development, developmental disorders, neuropsychology and neuroimaging (see Baddeley, 2007). The theory has nevertheless attracted numerous challenges. These include the explanation of the word length effect (e.g., Caplan, Rochon, & Waters, 1992; Caplan & Waters, 1994; Lovatt, Avons, & Masterson, 2000; Service, 1998), the phonemic similarity effect (Jones, Macken, & Nicholls, 2004), and the idea of short-term forgetting as time-based decay (e.g., Lewandowsky, Duncan, & Brown, 2004). There has also been controversy about the use of the phonological loop to explain the way unattended irrelevant sounds affect immediate recall (e.g., Jones, Hughes, & Macken, 2006) and there are competing theoretical accounts (e.g., Nairne, 2002; Neath, 2000). The phonological loop theory has been defended against these challenges (Baddeley, 2007; see also Mueller, Seymour, Kieras, & Meyer, 2003), but these arguments are tangential to our present focus. We are concerned here with two entirely uncontroversial shortcomings of the theory, namely its omission of mechanisms for serial order and long-term learning.

The absence of a mechanism for serial order prevents the phonological loop giving an adequate explanation for errors where an item is recalled correctly but in the wrong position in the list (Conrad, 1965). Such order errors are highly characteristic of immediate serial recall. They typically involve items migrating to adjacent positions, and are a principal determinant of the bow-shaped serial position curve (e.g., Henson, 1998). Order errors typically increase when items are phonemically similar (Conrad, 1965) and decrease when items are presented in rhythmic temporal groups, for example by adding an extra pause after every third item (Frankish, 1985; Ryan, 1969). Temporally grouping item presentation results in multiply-bowed serial position curves and a change in the distribution of order errors suggesting that order is coded at separate levels, between and within groups (McNicol & Heathcote, 1986).

The absence of a mechanism for long-term learning prevents the phonological loop from explaining numerous well-established effects of long-term knowledge in immediate serial recall, such as differences between words and nonwords and more subtle linguistic frequency effects (e.g., Gathercole, 1995; Gathercole, Pickering, Hall, & Peaker, 2001; Hulme, Maughan, & Brown, 1991). We have already noted that theoretical elaboration is also required to explain how short-term phonological storage contributes to vocabulary acquisition (Baddeley et al., 1998). In a recent revision of the working memory model, Baddeley (2000a) included an explicit link between the phonological loop and linguistic knowledge. However, the revision is pitched broadly and does not specify how the proposed link operates, making it difficult to generate testable predictions.

Recently, a number of attempts have been made to develop computational models of verbal short-term memory that go beyond the phonological loop theory by specifying mechanisms in more detail (see e.g., Botvinick & Plaut, 2006; Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1992, 1999; Farrell & Lewandowsky, 2002; Henson, 1998; Page & Norris, 1998). In general, these models have concentrated on addressing the problem of serial order, paying less attention to interactions between STM and LTM. Two exceptions that deal with both serial order and long-term learning are the connectionist models proposed by Botvinick and Plaut (2006) and Burgess and Hitch (1999). We focus here on our own model (Burgess & Hitch, 1999) showing first how a general understanding of the model can be used to derive novel predictions about sequence learning and then evaluating the model by testing these predictions experimentally. First we outline the way the model operates.

The Burgess and Hitch (1999) model implements the phonological loop as a localist neural network with two main components, a phonological/lexical store for item information and a context-timing signal that encodes the serial order of items. Phonological, lexical and timing information are represented in separate layers of nodes (see Fig. 1). Each node can transmit activation to nodes in adjacent layers according to the strengths of connections between them. Learning and forgetting occur through increases and decreases in the strengths of modifiable