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Original Articles

Control of information in working memory: Encoding and removal of distractors in the complex-span paradigm ☆

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ABSTRACT

The article reports four experiments with complex-span tasks in which encoding of memory items alternates with processing of distractors. The experiments test two assumptions of a computational model of complex span, SOB-CS: (1) distractor processing impairs memory because distractors are encoded into working memory, thereby interfering with memoranda; and (2) free time following distractors is used to remove them from working memory by unbinding their representations from list context. Experiment 1 shows that distractors are erroneously chosen for recall more often than not-presented stimuli, demonstrating that distractors are encoded into memory. Distractor intrusions declined with longer free time, as predicted by distractor removal. Experiment 2 shows these effects even when distractors precede the memory list, ruling out an account based on selective rehearsal of memoranda during free time. Experiments 3 and 4 test the notion that distractors decay over time. Both experiments show that, contrary to the notion of distractor decay, the chance of a distractor intruding at test does not decline with increasing time since encoding of that distractor. Experiment 4 provides additional evidence against the prediction from distractor decay that distractor intrusions decline over an unfilled retention interval. Taken together, the results support SOB-CS and rule out alternative explanations. Data and simulation code are available on Open Science Framework: osf.io/3ewh7.

1. Introduction

Working memory is a system for providing access to information for processing that can hold only a limited number of distinct representations at the same time (Baddeley, 2012; Cowan, 2005; Oberauer, 2009). The currently most popular experimental paradigm for studying working memory, and for measuring its capacity, is the complex-span task (Conway et al., 2005; Daneman & Carpenter, 1980). Complex-span tasks involve the interleaving of two competing tasks: Encoding elements of a list for immediate serial recall alternates with brief episodes of processing material that is typically unrelated to the memory list. For instance, participants could be asked to remember six consonants in their given order, and presentation of consonants alternates with arithmetic tasks (Turner & Engle, 1989), or with reading aloud a short series of words (Lewandowsky, Geiger, Morrell, & Oberauer, 2010). From here on, we will refer to the elements of the memory list as *memory items* or *memoranda*, and to the material to be dealt with in the interleaved processing episodes as *distractors*. The complex-span task is a popular tool for studying working memory because it combines several demands that theorists assume to tax working memory: Short-term maintenance combined with concurrent processing of unrelated material, and the need to minimize distraction by the processed material. Understanding how the cognitive system meets these demands is therefore an important milestone towards understanding the central role of working memory for cognition.

We recently developed a computational model of people's behavior in the complex span paradigm, the SOB-CS model (Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012). SOB-CS is an extension of the SOB model of serial recall (Farrell, 2006; Farrell & Lewandowsky, 2002) to complex span.[1] SOB-CS is a

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[1] SOB stands for "Serial Order in a Box", and CS for "Complex Span".

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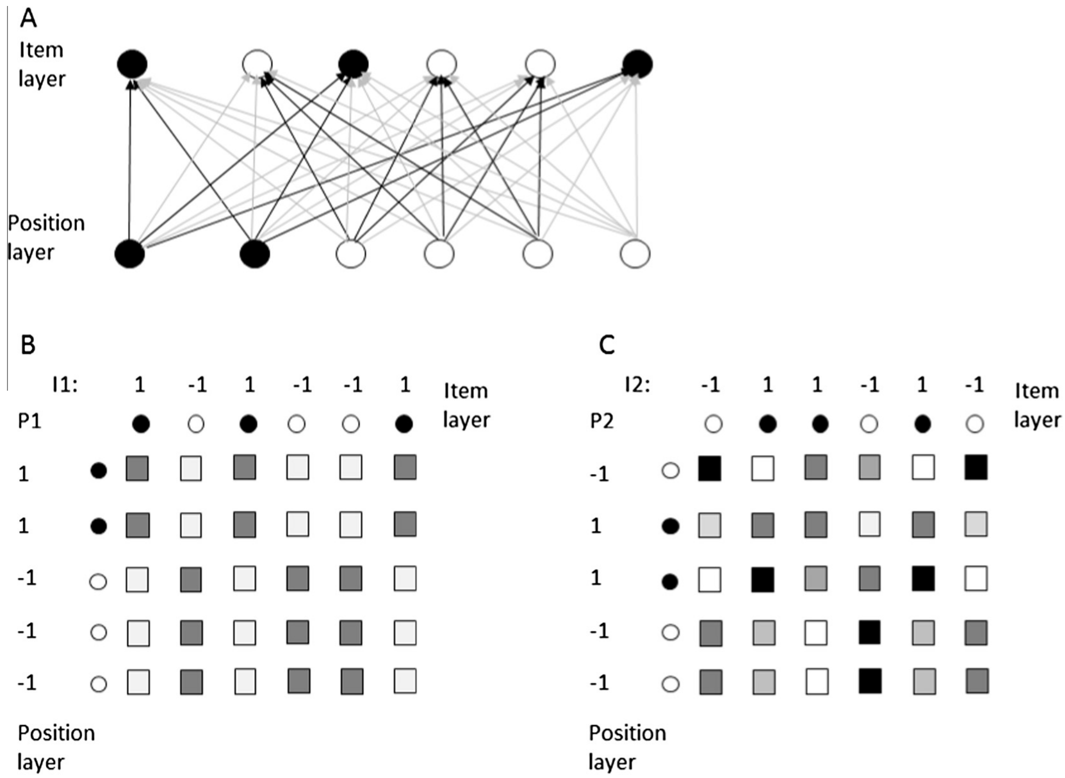

Fig. 1. Schematic of SOB-CS. (A) Two-layer neural network after acquiring the binding between one item and its position. Distributed representations are shown as patterns of activation across the units (shading of circles), and their bindings as patterns of connection weights (arrows). (B) The same state of the network as in (A), showing item and position representations as vectors and their bindings as matrix of connection weights. (C) The state of the network after encoding a second item by binding it to the second position. Superposition occurs in the binding matrix, which adds together the patterns of connection weight changes from each item-position binding.

two-layer connectionist network, with one layer for representing memory items and the other layer for representing their list positions (Fig. 1A). The model uses distributed representations for both items and positions. A memory list is encoded by binding each item to the corresponding list position through rapid Hebbian learning. For instance, the list ABCD is encoded by binding A to Position 1, B to Position 2, and so on. At recall, the model steps through the positions in the required recall order, using them as retrieval cues for the items bound to them.

In this model, the limited capacity of working memory arises from interference between distributed representations. There are two kinds of interference, interference by *confusion* and interference by *superposition* (Oberauer, Farrell, Jarrold, Pasiecznik, & Greaves, 2012). Interference by confusion means that the target item is confused with another element of the task vocabulary. The task vocabulary includes all potential recall candidates – for instance, when the task is to recall a list of consonants, then all consonants are elements of the vocabulary. Interference by confusion therefore can result in an order error (i.e., a transposition) when the target item is confused with another list item, or in an item error (i.e., recall of an extra-list item) when the target item is confused with an element of the vocabulary not in the current list.

In a complex-span task there is the possibility of confusing an item with a distractor, as long as the distractor is part of the vocabulary. For instance, in the classic reading-span task, in which participants read sentences and try to remember the last word of each sentence (Daneman & Carpenter, 1980), the non-final words of the sentences are distractors that arguably belong to the task vocabulary (i.e., words), and intrusions of such non-final words have been observed (Chiappe, Hasher, & Siegel, 2000; De Beni & Palladino, 2000; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998). In contrast, more recent versions of complex span use clearly different stimulus categories as memoranda and distractors – for instance, people read sentences and remember lists of letters. People hardly confuse letters with words at recall because words are not part of the vocabulary for letter recall. In SOB-CS, there is no interference by confusion between representations of clearly distinct classes, but there is still interference by superposition. Interference by superposition arises when multiple item-position bindings are encoded in the same matrix of connection weights between the item and the position layer (Fig. 1B). Because both items and positions are coded by distributed representations, their binding is a pattern of changes across the entire weight matrix. The pattern of weight changes that stores each binding distorts all other bindings that are stored in the weight matrix at the same time (Fig. 1C).

SOB-CS is based on two key assumptions that distinguish this model from other models of working memory: First, representations of the distractors, as well as other representations generated during the processing episodes, are obligatorily encoded into working memory (cf. Logan, 1988), thereby adding to the interference in the system. Specifically, distractor representations are associated to the position of the immediately preceding item, so that they interfere most with that item. To the degree that position representations overlap with neighboring positions, interference spreads to neighboring list items. Second, when there is free time following processing of a distractor, that time can be used to remove the distractor representation from working memory, thereby reducing the amount of interference with the memoranda. The first assumption explains why performance on complex-span tasks is worse than on simple-span tasks, which test immediate recall without an additional processing assignment. The second assumption explains why complex-span performance is better