respect, nonword repetition continues to serve as a valuable tool for researchers and clinicians interested in SLI.

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Shelley Gray Arizona State University

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Nonword repetition, phonological storage, and multiple determination

The proposals that (a) nonword repetition and word learning both rely on phonological storage and (b) both are multiply determined are two of the major foci of Gathercole's (2006) Keynote Article, which marshals considerable evidence in support of each. In my view, the importance of these proposals cannot be overstated: these two notions go to the heart of the relationship between nonword repetition and word learning. Indeed, they figure prominently in the approach that my colleagues and I have taken to studying that relationship (e.g., Gupta, 2006;

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Gupta, Lipinski, Abbs, & Lin, 2005; Gupta & MacWhinney, 1997). An important aspect of our approach has been the attempt to construct a computational model that can simulate performance in a nonword repetition task and in a word learning task, the rationale being that a computational model that achieved this would constitute a proposal about the *processing mechanisms* that may underlie the relationship. In this Commentary, I describe how our computational work offers a concrete way of thinking about *how* nonword repetition and word learning may rely on phonological storage, and about *how* these abilities may be multiply determined. Such computational work is, I suggest, a valuable tool in further investigating the important relationship that has been revealed by Gathercole's influential work, and that is analyzed in the Keynote Article.

The question of how nonword repetition might rely on phonological storage leads directly, as in Gathercole's discussion (2006), to the question of how performance in a nonword repetition task might be related to performance in immediate serial recall, the canonical phonological storage task. In addressing this question, my colleagues and I have pointed out (Gupta et al., 2005) that the functional requirement for performance of either task is the immediate encoding and retrieval of the serial order of a novel phonological sequence, which in immediate serial recall is a novel sequence of words or digits, and in nonword repetition is a novel sequence of sublexical units such as phonemes and/or syllables. The mechanism(s) of phonological storage underlying performance in these tasks must therefore necessarily be concerned with computing serial order. In the one case, however, the serial ordering is at the level of lexical representations (lists of word forms, in immediate serial recall). In the other case (nonword repetition), the serial ordering is at the level of sublexical constituents. Phonological serial ordering must therefore be capable of operating at both levels of representation: lexical and sublexical.

This means that a computationally specified account that simulates performance in both tasks must provide some basis for *representation* of both lexical and sublexical information (in addition to specifying the basis for serial ordering for both types of information). That is, the account must incorporate the kinds of representational distinctions that are the stuff of (psycho)linguistics. One approach here might be to propose a bufferlike phonological storage device into which sequences of representations are copied, no matter whether they be sequences of words, or syllables, or phonemes. In our own work, we have adopted a different approach. As shown in Figure 1, our model incorporates word form and semantic levels of lexical representation, and syllabic and phonemic levels of sublexical representation, and thus encompasses much of what is typically included in psycholinguistic models of lexical processing. In keeping with this, the connection weights between units at these various levels of representation instantiate what is, in effect, long-term linguistic knowledge in the system, both phonological and semantic.

The presentation of a word form to the model (depicted by the "speech input" arrows in Figure 1) results in sequences of representations being activated at the various levels of representation. For instance, presentation of the word form *zitricaymus* is manifested in the model as activation of the relevant sequence of phoneme representations at the phoneme level, activation of the relevant sequence of syllable representations at the syllable level, and activation of the relevant word



Figure 1. A model of nonword repetition and immediate serial recall (Gupta, 2006).

form representation at the word form level. New representations are created on the fly as necessary at each of these levels. Presentation of either a known word form or a novel word form thus gives rise to sequences of activations at the phoneme and syllable levels, and of a single activation at the word form level. A "list" is simply a sequence of these sequences. For instance, presentation of the list {*cat dog ball chair*} leads to activation of the sequences of phonemes and syllables constituting each word in the list, and additionally, gives rise to a sequence of activations at the word form level (the representations of the word forms cat, dog, ball, and chair). Thus, in a real sense, a word form is just a list of length one.¹ The model also incorporates a serial ordering mechanism that encodes and retrieves the serial order of a sequence of activations, at any level of representation it is connected to. Details of its operation are provided elsewhere (Gupta, 2006; Gupta & MacWhinney, 1997); for present purposes, the main points to note are as follows. First, the encoding does not involve making a copy of the elements

of the sequence; rather, it consists of a connection weight-based encoding, in the connections from the serial ordering mechanism to the word form and syllable levels of representation. Second, because these connection weights decay, the encoding is strictly short term. Third, following presentation and encoding of a sequence in this manner, recall takes the form of "replaying" the previously encoded sequence at the same level of representation where it occurred, that is, in the linguistic system, via the short-term connection weights; thus, it is important that encoding and retrieval engage not only the serial ordering device but also the linguistic system as well. As shown in Figure 1, the serial ordering mechanism has connections to both the word form and syllable levels of representation, and can thus encode and retrieve the serial order of sequences of activation that occur at either of these levels. Thus, the model provides for serial ordering at both lexical and sublexical levels of representation; that is, it can perform both immediate serial recall and nonword repetition. In response to presentation of a list, or a word, or a nonword, it can repeat the list/word/nonword, with the output being serially ordered sequences of phonemes within (if appropriate) a serially ordered sequence of syllables within (if appropriate) a serially ordered sequence of words.

In simulations, this model exhibits several key characteristics of immediate serial recall and nonword repetition (Gupta, 2006). For immediate serial recall, these include serial position effects, list length effects and positional gradients for movement errors. For nonword repetition, they include a decrease in accuracy with nonword length, and the syllable-wise serial position effects that have recently been documented in repetition of individual polysyllabic nonwords (Gupta, 2005; Gupta et al., 2005). Furthermore, the model's nonword repetition performance is correlated with its immediate serial recall performance (Gupta, 2006). Thus, as gauged by its correspondence with human behavior, the model as thus far developed appears plausible.

How does this computational model relate to Gathercole's (2006) two proposals? The dependence of nonword repetition on phonological storage is very directly realized in this model: the serial ordering mechanism, which provides for phonological storage, is crucial for nonword repetition, as well as for the canonical phonological storage task of immediate serial recall. This has been confirmed in the model by disrupting operation of the serial ordering mechanism, which grossly impairs immediate serial recall and nonword repetition performance, but, as in "pure short-term memory" patients (Vallar & Baddeley, 1984), leaves intact the repetition of known words (which in the model are encoded by long-term connection weights between the semantic/word form/syllable layers). The dependence of word form learning on phonological storage arises because what *gets* encoded in the long-term connection weights over multiple exposures depends on the accuracy with which that sequence is encoded in the first place, as a nonword, and that depends on phonological storage.

Nonword repetition performance, is also, however, critically dependent on many other components of the model. Nonword repetition performance will depend, for instance, on the effectiveness of the long-term knowledge of syllables, incorporated in the model's connection weights from the syllable to the phoneme level. The efficiency of word form *learning* will also depend on the effectiveness of those connection weights, and additionally on the effectiveness of long-term knowledge

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of word forms as a whole, incorporated in the model's connection weights from the word form to the syllable level. In addition, word learning, comprising learning of not only a word form, but also an association between the word form and a semantic representation, is clearly dependent on learning in the connections between the semantic and word form levels of representation. The model thus offers a concrete realization of the notion that nonword repetition and word learning are both multiply determined. Of interest, the model's instantiation of multiple determinations also offers a resolution of the debate between the phonological sensitivity and phonological storage hypotheses described in the target article. In the model, there is no opposition: *both* have a role to play. The role of phonological storage has already been discussed. The role of phonological sensitivity (or more generally, linguistic experience) arises because the development of long-term linguistic knowledge itself increases the effectiveness of the long-term connection weights between the various linguistic levels, facilitating additional learning that is possible between those levels of representation, and thus facilitating both nonword repetition and word learning. The model's concretizaton of the notion of multiple determinations thus suggests that the controversy over phonological storage versus phonological sensitivity may be misplaced.

This last point serves as an appropriate place to conclude this Commentary. I believe it nicely illustrates the theoretical importance of Gathercole's (2006) proposals; it also illustrates the value of computational work in further investigation of these important phenomena.

NOTES

1. For a list or a single word form, the activated representation(s) at the word form level will lead to activations at the semantic level of representation. For known word forms, these will be the specific semantic representation that is associated with that word form, whereas for nonwords the evoked semantic representation will tend to be an indeterminate semantic representation that is a blend of those corresponding to known word forms that are similar to the nonword.

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Prahlad Gupta University of Iowa