Is the Phonological Loop Articulatory or Auditory?

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Abstract

The paradigm of *immediate serial recall* (Baddeley, 1986) has been used extensively in investigation of working memory, but its relation to and implications for the nature of *phonological processing* have seldom been examined. We show that findings from this domain can be interpreted in two ways, and relate these two interpretations to a simple model of phonological processing. One interpretation emphasizes the availability of information from "output" phonological processing to "input" phonological processing, while the alternative account stipulates no such connections. On the basis of an experimental study designed to choose between the two accounts, we tentatively conclude that the interpretation suggesting output-input connectivity is supported. Establishment of this result would be of considerable interest, since it indicates that processes in language production can impact directly on processes in language perception.

Introduction

In *immediate serial recall* (ISR) tasks, the subject is presented with sequences of *unrelated* verbal items (such as digits or words), and is required to recall the sequence in correct order, immediately following its presentation. Presentation of the list may be either auditory or visual. The subject may be required to respond either in speech, or in writing, or in some other fashion.

This task domain has played a central role in development of the *working memory* model of Baddeley (1986). In this model, the component of working memory dealing with auditory-verbal short-term memory is what has been termed the "articulatory loop", and more recently, the "phonological loop". This system is supposed to underlie the performance of ISR tasks.

The articulatory loop system is comprised of the following elements (Baddeley, 1990). (1) A phonological input store within which memory traces will fade if not revived within 1-2 seconds. (2) An articulatory control process ("articulatory rehearsal") which serves two functions: (a) maintaining memory traces within the phonological store, by means of subvocal rehearsal, and (b) providing for visually presented items to be fed into the phonological store, provided they are capable of being encoded phonologically and subvocalized. Subvocal rehearsal is a process which operates in real time, with long words taking longer than short.

A major question concerning the current formulation of the "loop" is the nature of the process that refreshes stored representations. As we will argue, the accepted interpretations of the data as evidence for an "articulatory" process are somewhat problematic[1]. Moreover, although this model posits an informational flow from an output phonological process to a phonological representational system, it seems to have been assumed that this is a specialized "articulatory rehearsal" process not having any necessary relation to normal articulatory processes. In any case, there has been, as Monsell has noted, "...a curious reluctance to specify with any precision ... [its] relation to ideas about the lexicon ..." (Monsell, 1987, p.283).

In this paper, we first relate the phenomena of ISR to possible models of phonological processing, showing that the standard interpretation of the data implies the availability of information from "output" phonological processing to "input" phonological processing[2]. We then show, however, that there are alternative accounts of the data, and describe an experiment designed to discriminate between the alternatives.

The articulatory loop

A number of phenomena have motivated and influenced thinking about the "articulatory loop". Of these, the following are most pertinent to the present discussion. Note that the effects are discussed here with respect to presentation of recall stimuli through the *auditory* modality only.

1. **The phonological similarity effect.** In immediate serial recall of lists of words, sequences of similar sounding words are recalled in correct order much less frequently than sequences of dissimilar words of comparable frequency and length (Baddeley, 1986).

2. **The irrelevant speech effect.** Immediate serial recall of auditorily presented stimuli is disrupted by the presentation of irrelevant spoken material that the subject

[1] It appears well established that this process cannot be articulatory in the sense of involving the speech musculature; rather, "articulatory" connotes that the process is somehow involved in phonological production *planning* (Baddeley, 1990), and it is in this sense that we will use the term "articulatory" or "output". We will argue, however, that accepted interpretations are problematic even with respect to this narrower sense of the term.

[2] As has been previously suggested by Monsell (1987).

is free to ignore. The important disruptive characteristics of the unattended material appear to be phonological, with nonsense syllables being just as disruptive as meaningful words (Baddeley, 1990).

3. **The word length effect.** Immediate serial recall performance of word sequences deteriorates as the constituent words in the sequence become longer.

4. **The concurrent articulation effect.** When the subject is required to articulate an irrelevant sound during list presentation, immediate serial recall is markedly impaired (Baddeley, 1990). With auditory presentation, the *phonological similarity effect* is still observed under concurrent articulation, while the *irrelevant speech effect* seems to be somewhat preserved, at least under certain conditions (Hanley and Broadbent, 1987). Under concurrent articulation the *word length effect* is abolished if concurrent articulation is required during both list input and recall (Baddeley et al., 1984).

These phenomena have a standard interpretation in terms of the working memory model. The relevant part of this interpretation for present purposes is that there is an "articulatory rehearsal" process, i.e., an *articulation-based process* that can be invoked to "refresh" *phonological representations* of the recall items. This interpretation is taken to be supported by the effect that concurrent articulation has on immediate serial recall performance: concurrent articulation is presumed to impair recall performance because it makes articulatory or "output" processes unavailable, or less available, for rehearsal.

Processing spoken words

Before exploring the implications of immediate serial recall for views about the phonological processing of single spoken words, we need to specify a framework within which to think about such processing. This section presents a bare-bones model that makes as few assumptions as possible. It is intended to provide a skeletal architecture that should be uncontroversial. The model is shown in Figure 1. Its basic "processing" systems are assumed to be the Auditory Perceptual System and the Articulatory System. Resulting from these processing activities are "input phonological representations", and "output phonological representations"[3], with the former being more closely related to the Auditory System and the latter more closely related to the Articulatory System. "Input phonological processing" leads to activation of a "lexical phonological representation". Note that this could involve processing activity in both the Auditory and Articulatory systems, but with the Auditory System assumed to be the starting point in such activity. "Output phonological processing" is assumed to begin with an evoked "lexical phonological representation", and to end with the production of a spoken word; thus the Articulatory System is the ultimate output point in such processing, but again, the processing could involve activity of both the Auditory and Articulatory systems.

[3]Corresponding to what Monsell has termed the "domains" of *input phonology* and *output phonology*.

On hearing a word, acoustic input arriving in the Auditory System results in activation of the word's lexical phonological representation. This representation provides input that the Articulatory System can convert into a sequence of articulatory gestures; this provides the basis for *repetition* of a word. Volitional *production* of a word begins with activation of a particular lexical phonological representation (for example, as a result of activation from semantics). This representation feeds forward toward the Articulatory System, which eventually produces the appropriate sequence of articulatory gestures.

It is assumed that hearing a non-word results in activation of a phonological representation that of course does not correspond to any known word but nevertheless can provide a basis for articulation, i.e., for repetition. *Learning* a new word involves developing a lexical phonological representation of the word.

This minimalist model provides for the basic abilities necessary in the processing of single words, while making as few debatable assumptions as possible. For example, it is neutral with respect to the degree of discreteness or interactivity of "input" and "output" processing. It assumes that there is a flow of information from "input" phonological processing to "output" phonological processing, which hardly seems controversial. Of course, the model is greatly underspecified. Nevertheless, it provides the basic conceptual structure within which exploration of more specific quesions can proceed.

Finally, the conception of short-term storage adopted here needs to be clarified. Short-term storage is viewed as a process in which "representations" are entered into a "loop" of activations, maintenance of which requires that representations must be *re-entered* into the loop, which requires that they be "refreshed". The details of this processing are not important for present purposes; they are discussed in more detail in (Gupta, 1992), and are functionally similar to those employed in (Burgess and Hitch, 1992). The points to note are that (a) evoked representations can (but do not automatically) form input to the short-term memory, (b) the short-term memory can temporarily learn *sequences* of stimuli appearing as input, and (c) the memory of sequences decays rapidly unless the inputs to the system are re-presented, i.e. "refreshed". It is also assumed that presentation of an input to a short-term system can only occur when a stimulus is not simultaneously entering the associated long-term representational system. It is interesting to note that this system appears similar to Hebb's notion of short-term memory as reverberation in a "closed loop" (Hebb, 1949).

"Input" and "output" phonological processing and immediate serial recall

The specific question focussed on in this paper is the extent to which information about the products of "output" phonological processing might be available to "input" phonological processing. A variety of kinds of evidence have traditionally been adduced in support of the existence of such an *output* → *input* flow. Among these are data on speech monitoring, on repetition priming, on sub-

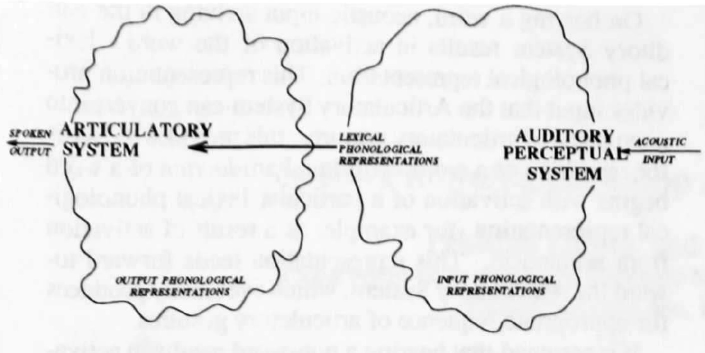

Figure 1: Basic model of the processing of single spoken words.

lexical influences of production on perception, and the dissociation between receptive and productive vocabulary in language learning (Monsell, 1987).

The standard interpretation of immediate serial recall effects reviewed above is that there is an "output-process" mediated "refresh" of "input phonological" representations[4]. Viewed against the outline model of Figure 1, this can be seen as implying that "output" phonological processing can provide informational input to "input" phonological processing, i.e., it implies the existence of "output-input" connections complementing the "input-output" connections already shown in the figure.

If the above interpretation of the ISR data is correct, therefore, results from this task domain provide clear indications regarding the broad architecture of the "phonological processing" system. Their relevance to phonological processing has, of course, been recognized previously, notably by Monsell, who suggested that rehearsal involves cycling information between input and output phonological buffers, using the same processes that are involved in the usual processing of words and nonwords (Monsell, 1987). The domain of ISR has also been used to investigate the relation of the "phonological store" postulated by the working memory model to phonological representations involved in the normal input processing of words (Berndt and Mitchum, 1990).

What does not appear to have received much previous critical examination, however, is the validity of the basic interpretation of the ISR data. Although this received interpretation is in terms of an output-process-based refresh, the data do not in fact uniquely support such an interpretation. This is relevant because, if the data can be accounted for without assuming input-output connections, then one of the sources of support for such connections is removed.

Logically, the effects of concurrent articulation could have any or all of the following components: (1) depletion of "output processing" resources that would otherwise have been (more) available for rehearsal, (2) depletion (because of having to perform a secondary task) of a *general* processing capacity that is involved in immediate serial recall, and (3) creation of auditory stimuli, which undergo phonological coding and thus interfere with the actual serial recall stimuli – an irrelevant speech effect.

The standard interpretation of ISR data attributes the effects of concurrent articulation to the first of the above factors: the depletion of articulatory resources. The second factor above has also been examined. In a control condition for general processing load, subjects were given the concurrent task of finger-tapping instead of concurrent articulation; this control task had little or no effect on STM performance (Baddeley, 1990). Assuming that finger-tapping is in fact the appropriate control, this would seem to rule out the effect of processing load as the factor underlying concurrent articulation effects. That leaves the third factor above: the auditory interference that might be created by concurrent articulation.

An account of the concurrent articulation effect can, in fact be provided in terms of a model that assumes only "input-process refresh" of input representations, and that attributes the effects of concurrent articulation to auditory interference – essentially, an irrelevant speech effect, created by the subjects' own irrelevant concurrent articulations. Unlike the "output-process" refresh account, this account does not implicate "output-input" connectivity[5]. In what follows, we outline both the "output-refresh" and "input-refresh" accounts, discussing their explanations of the various effects obtained in ISR tasks.

The articulatory account. According to what we will term the *articulatory* account, "rehearsal" in immediate serial recall involves the refreshing of input phonological representations (lexical phonological representations, in terms of Figure 1) by an output phonological process; these representations form the input to an associated short-

[4]A logical possibility is that output phonological processes refresh *output* phonological representations; however this possibility is difficult to maintain in light of human speakers' simultaneous translation and speech shadowing abilities. This suggests that the phonological representations involved in "rehearsal" are "input" rather than "output" representations. For fuller discussion, see (Monsell, 1987; Shallice and Vallar, 1990; Gupta, 1992).

[5]It might be objected that, within the working memory model, there are several converging lines of evidence for the existence of "output-process refresh". Consequently, it might be argued, even if the individual phenomenon of concurrent articulation were amenable to an "auditory interference" account, such an account would not accommodate the various other data that can be accounted for in terms of "articulatory rehearsal". Two points are worth making in this regard. *First*, a large component of the data usually adduced in support of articulatory rehearsal derives from ISR with *visual* presentation. However, the relevant interpretations of these data are crucially dependent on a variety of assumptions about how visually-presented verbal stimuli undergo "phonological coding", and are thus far from secure. In particular, it has been shown that phonological encoding of visual stimuli can occur even under concurrent articulation (Besner, 1987), and this renders the working memory model account of ISR with visual presentation problematic, even if further assumptions are made, as in (Baddeley, 1986). *Second*, if only the data from ISR with *auditory* presentation are taken into account, then, as shown below, all the ISR phenomena dicussed above can be accounted for within an "input-process refresh" model.

term memory system[6]. In this account, the ISR task normally involves such output-process-mediated rehearsal, and irrelevant concurrent articulation affects ISR performance because it reduces the availability of the articulatory resources needed to perform this refresh. According to this account, *phonological similarity effects* would occur in the local (STM) loop. Since phonologically similar words would have similar representations, they would be more confusable than phonologically dissimilar words, amongst the rapidly-formed and rapidly decaying associations of the STM. The *word length effect* would reflect the fact that longer words take longer in their output processing, as a result of which their transmission time around the global feedback loop would be greater than for shorter words. Consequently, longer words would be refreshed less frequently than shorter words would be, and the short-term associative STM weights decay more. The *irrelevant speech effect* would arise because it reduces the number of time slots available for entry of phonological system representations into the local loop for rehearsal. This is because, as noted above, this entering of representations into a short-term store is assumed possible only when a stimulus is not entering the associated long-term store. Thus, although unattended stimuli do not themselves get entered into the STM loop, they reduce the opportunities for recall stimuli to be so entered. *Concurrent articulation* is viewed as reducing the availability of output processing mechanisms. Output processing for "refresh" purposes can therefore only be undertaken in between repetitions of the concurrently articulated item. This has the effect of reducing the opportunities for recall stimuli to be refreshed, and thus entered into the STM loop.

Note that both irrelevant speech and articulatory suppression reduce the opportunity for refreshed representations to enter the STM loop, but for different reasons, representing different "bottlenecks". With irrelevant speech, the bottleneck is at the point of entry of refreshed representations into the STM loop, while under articulatory suppression, the bottleneck is in the refresh process itself. Note also that articulatory suppression could have an irrelevant speech effect as well.

Under concurrent articulation, there should be no change in the phonological similarity effect, since representations are still subject to phonological confusability. Reduction of the word length effect occurs because words can only be refreshed between concurrent articulations. The effect of this is to fix the refresh rate of stimuli at a constant rate, irrespective of whether they are long or short, so that word length effects will be abolished[7]. Finally, irrelevant speech might result in a further deterioration in performance, given that it will tend to impose a second bottleneck. However, whether there is an additive effect or not will depend on the relative synchrony of the irrelevant speech and the suppression responses.

The auditory account. According to an *auditory* account, there would be some kind of "mental echo" of the auditorily presented stimuli. This would be analogous to the visual imagery that subjects have reported using with visually presented stimuli (Baddeley et al., 1975). The "mental echo loop" consists of the "replaying" of auditory images of stimuli, resulting in the refreshing of their input phonological representations. Importantly, in this account, this mental echo process does not depend in any way on output processing mechanisms. *Phonological similarity effects*, as in the articulatory account, would occur in the local phonological loop. In this view, the process of "replaying" a stimulus takes longer for longer words. Consequently, the lexical phonological representations of longer words are refreshed less frequently than those of shorter words would be, and the short-term associative weights decay faster. The *word length effect* would then reflect the fact that longer words take longer to echo. As a result, their transmission time around the "echo loop" would be greater than for shorter words, and so longer words would be refreshed less frequently than shorter words. The account of the *irrelevant speech effect* would be identical to the one in the articulatory model above: the irrelevant speech effect would arise because it reduces the number of time slots available for entry of lexical phonological representations into the STM loop for rehearsal. *Concurrent articulation* in this account would be viewed as causing an irrelevant speech effect. It would therefore reduce the opportunities for recall stimuli to be entered into the STM loop, exactly as in the irrelevant speech effect. Under articulatory suppression, there should be no change in the phonological similarity effect. The word length effect would be abolished or reduced because the irrelevant speech effect created by articulatory suppression would impose a bottleneck on when refreshed representations could be entered into the STM loop, and this would tend to affect long and short words equally. Presentation of irrelevant speech might or might not result in further deterioration in performance, depending on the extent to which it was synchronized with the suppression responses.

Discriminating between the accounts

The obvious question is how to discriminate between the two accounts. It is useful to begin by examining the differing analyses of concurrent articulation more closely.

[6] It should be noted that this account is essentially a translation of the standard "articulatory loop" account into the framework of our simplistic phonological processing model.

[7] Assume the suppression response takes X msecs, and is repeated at the rate of once every second. Then in every second, there is a fixed $1000 - X = Y$ msec period during which to perform rehearsal of a recall word via output processing. It seems realistic to assume that Y is only long enough for articulatory processing of one word, so that, irrespective of its length, only one word can be rehearsed per time period. In case short words are short enough that two can be rehearsed in time period Y, or in case long words are long enough that they can be only partially rehearsed in time period Y, then there could still be word length effects, and so the account can accommodate the possibility mentioned in (Baddeley, 1986, p.83-84) of some remaining word length effect even under articulatory suppression.

As noted earlier, the effects of concurrent articulation can be analyzed into three components: (1) usage of general resources resulting from having to perform a motor task, (2) creation of auditory interference, and (3) usage of articulatory resources.

In explaining the impact of concurrent articulation on ISR, both the articulatory and auditory accounts are consistent with effects due to general resource competition, and auditory interference. Where they differ is in whether they allow for a role for articulatory resource competition. The articulatory account postulates articulatory resource competition, since in this view, ISR draws on articulatory resources. The auditory account disallows articulatory resource competition, since in this view, no articulatory processes are involved in ISR.

This suggests a means of discriminating between the two accounts. According to the auditory account, if we control for components (1) and (2) above of concurrent articulation with a *non-articulatory* task, then ISR performance under this non-articulatory control task will be equivalent to ISR under concurrent articulation. The articulatory account, on the other hand, predicts that ISR under this control task will be superior to that under concurrent articulation.

The question is determining the right controls. According to Baddeley (1986), *finger-tapping* is an appropriate control for the general resource demands of concurrent articulation. An appropriate control for the auditory interference created by concurrent articulation should be exposure to repeated utterances of the same speech sound that is articulated during concurrent articulation. Combining these with ISR creates a task that should discriminate between the two hypotheses. In this task, subjects would have to perform ISR while (i) concurrently tapping a finger, and (ii) hearing repeated utterances of a speech sound. If general resource demands and auditory interference have been controlled for, then this task differs from performance of ISR under concurrent articulation only in its usage of articulatory resources.

Figure 2 shows the predicted relation between ISR span size under concurrent articulation (Condition A) and ISR span size under the concurrent control task (Condition B), under each of the two accounts. The auditory account predicts no difference between conditions, while the articulatory account predicts worse performance in Condition A.

Experimental procedure

To test these predictions, we devised an experiment based on the logic just outlined. Subjects in this experiment were 36 undergraduate students at Carnegie Mellon University, who participated in the experiment for course credit.

There were two conditions in the experiment. In both conditions, the subjects' primary task was to recall sequences of digits that were presented to them auditorily. In addition, subjects were required to perform the following secondary tasks. In Condition A, subjects were asked to articulate the word *the* while performing the recall task.

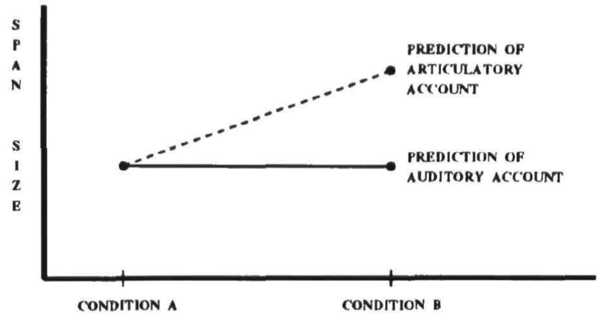

Figure 2: Predicted span sizes. The *articulatory* account predicts that span size will be lower in ISR under concurrent articulation (Condition A), than in ISR with concurrent finger-tapping and auditory interference (Condition B). The *auditory* account predicts that there will be no difference.

In Condition B, subjects were required to tap their finger while performing the recall task; in this condition, subjects were also played a recording of repeated utterance of the word *the*.

For the immediate serial recall task, the stimuli were auditorily presented sequences of digits. Sequences varied in length from four digits to eleven digits, with one trial consisting of presentation of one sequence of a particular length. For example, at list length four, one trial consisted of auditory presentation of a sequence of four digits such as *three, eight, two, five*. There were eight trials at each list length. Presentation of the lists began with sequences of four digits. If a subject recalled in correct serial order five or more of the eight sequences (trials) at a particular list length, the next higher list length was introduced. At the beginning of trials of each list length, the subject was told what the length of sequences would be. The longest list length for which a subject correctly recalled five or more sequences was taken as the measure of that subject's digit span.

Presentation of each digit sequence (trial) was computer controlled. One token of each of the digits *one* through *nine* spoken by a female native speaker of American English was recorded as digitized sound on a Macintosh computer. Random sequences of these tokens were generated, and presented auditorily under computer control, at the rate of one digit per second. Subjects were seated facing the computer screen, on which a cross appeared after presentation of each sequence. Subjects were instructed to repeat the sequence orally, in order, as soon as the cross appeared. The experimenter wrote down the subjects' responses, without providing any feedback about their accuracy. Initiation of each trial was controlled by the experimenter, when the subject was ready.

In the secondary task in Condition A, subjects were required to concurrently and repeatedly articulate the word *the*, throughout presentation of each sequence of digits, until the point when spoken recall began. At the beginning of the condition, subjects were played a recording of the word *the* being repeated every 500 msec, and practiced articulating *the* in synchrony with the recording. They were asked to maintain that same rate of articulation during the actual experimental procedure.

In the secondary task in Condition B, subjects were required to concurrently tap the index finger of their dominant hand, throughout presentation of each sequence of digits, until the point when spoken recall began. At the same time, a recording was played of the word *the* being repeated every 500 msec, which subjects were instructed to ignore. However, they were instructed to tap their finger at the same rate as the repetitions of *the*. The recording was turned on by the experimenter at the start of each trial, and was turned off as soon as the cross appeared on the computer screen, indicating that the subject should respond.

The experimental design was a within-subjects repeated measures design. Each subject performed the ISR task under Condition A as well as under Condition B. Each subject was randomly assigned to one of the two possible treatment orders.

Results and analysis

As noted above, subjects' digit span in each condition was taken to be the greatest list length at which they performed correctly on five or more of the eight trials.

Mean digit span in Condition A (concurrent articulation) was 5.89, while mean digit span in Condition B (finger tapping + irrelevant speech) was 6.97. The difference was highly significant ($F(1,35) = 48.09, p < 0.0001$).

This result is consistent with the predictions of the articulatory account, but not the auditory account. That is, the results support the notion that depletion of articulatory resources plays a role in the effect of concurrent articulation on immediate serial recall performance. This, in turn, supports the idea that "rehearsal" during normal ISR does involve "output-based" phonological processing resources that refresh input phonological represenations; and this, in its turn, supports the existence of *output* $\rightarrow$ *input* connectivity in phonological processing.

Of course, this interpretation of our results is crucially dependent on two assumptions. First, we have assumed that the finger tapping task in Condition B of our experiment is in fact an appropriate control for the general processing load imposed by concurrent articulation in Condition A. Second, we have assumed that exposure to repeated utterances of *the* in Condition B is a good control for any auditory interference effects of concurrent articulation in Condition A. We are currently pursuing further research to test both these assumptions.

Discussion

In this paper, we have attempted to relate immediate serial recall to possible models of phonological processing. The standard interpretation of these phenomena implies the availability of information from "output" phonological processing to "input" phonological processing, but there is an alternative account of the same phenomena that does not imply the existence of such a flow. Findings from the ISR paradigm may therefore provide some of the clearest indications bearing on the issue of phonological input/output relations

We presented the results of an experimental study aimed at distinguishing the two accounts, and tentatively concluded that the results support the received interpretation, which implies *output* $\rightarrow$ *input* connectivity in phonological processing. Of course, a number of questions remain unresolved, and we are currently pursuing further research to further test the accounts, as well as the assumptions of our experiment.

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