

RETROACTIVE EFFECTS OF IRRELEVANT SPEECH

Retroactive Effects of Irrelevant Speech on Serial Recall from Short-Term Memory.

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Abstract

Five serial recall experiments are reported. In four of the five it is shown that irrelevant sound (IS) has a retroactive effect on material already in memory. In the first experiment, IS presented during a filled retention interval had a reliable effect on list recall. Four further experiments, three of which used retroactive IS, showed that IS continued to have an effect on recall following a long, filled retention interval. Articulatory suppression during visual input was found to abolish the long-lasting, retroactive effect of IS, supporting the idea that IS affects the phonological loop component of short-term memory. IS also, therefore, seems to affect a longer term memory system with which the loop interacts.

Even when stimuli are presented visually, the presence of irrelevant sound (IS) significantly impairs performance on immediate serial recall (Colle, 1980; Colle & Welsh, 1976). The detailed pattern of interaction between IS and other factors influencing memory performance (Baddeley, 2000a; Jones & Macken, 1993; Hanley 1997; Jones, Madden & Miles, 1992; Larsen, Baddeley & Andrade, 2000; Larsen & Baddeley, in press; Macken, Mosdell & Jones, 1999; Miles, Jones & Madden, 1991; Neath, 2000; Salamé & Baddeley, 1982, 1986, 1987, 1989) has been seen as placing important constraints on the development of models of short-term memory such as the working memory model (WM) (Baddeley, 1986; Baddeley & Hitch, 1974), Jones's (1993) object-oriented episodic record (O-OER) model and Nairne's feature model (Nairne 1990; Neath, 2000). However, the fundamental question of the locus and mechanism of the IS effect has still not been satisfactorily resolved.

Both Salamé and Baddeley (1982) and Hanley (1997) found that there was no effect of IS for visually presented lists when subjects were required to perform articulatory suppression during presentation and recall of those lists. Salamé and Baddeley interpreted their results within the WM model. They assumed that IS interfered with the contents of the phonological store and, for visual presentation, the effect of IS could be eliminated if articulatory suppression prevented phonological recoding of visual material. For auditory material, they argued that suppression should not eliminate the IS effect because auditory information has direct access to the phonological store. This prediction was confirmed by Hanley and Broadbent (1987) and Salamé & Baddeley (1986). The assumption that IS interferes with the contents of the phonological store seems to imply that the phonological similarity (PS) between the IS and the information to be remembered

should be a crucial factor in determining the magnitude of the interference. However, this turned out not to be the case (Bridges & Jones, 1996; Buchner, Irmen & Erdfelder, 1996; Jones & Macken, 1995; Larsen, Baddeley, & Andrade, 2000; LeCompte & Shaibe, 1997). Almost all of the early work on IS had used speech as the irrelevant sound, however, a range of irrelevant sounds other than speech can also lead to poorer memory for order (Jones & Macken, 1993; Klatte, Kilcher, & Hellbrück, 1995; Salamé & Baddeley, 1989). Although these results do not necessarily contradict the WM assumption that IS has its effect on the phonological store, they do highlight the need for an explanation that goes beyond positing direct phonological interference. A model consistent with both the WM framework and these seemingly difficult data has recently been proposed by two of the authors (Page & Norris, in press) and we will return to this later.

A rather different explanation of the effect of IS is given by Jones (1993) in his object-oriented episodic record (O-OER) model. In this model, order is maintained by a series of pointers to objects in memory. IS sets up another series of pointers. Interference between the two sets of pointers leads to errors in tracing the order of information to be recalled. An important feature of the O-OER model is that there is functional equivalence between verbal and spatial information in short-term memory (Jones, Farrand, Stuart & Morris, 1995). According to this view, serial order is stored in short-term memory in a general workspace regardless of stimulus modality. In addition, Macken and Jones (1995) claim that IS should have the same effect on memory as does articulatory suppression, given that both impair recall by setting up competing streams in memory. The claim that IS and articulatory suppression have equivalent effects has been challenged in a number of

recent papers (Hanley & Bakopoulou, 2003; Larsen, Baddeley & Andrade, 2000; Larsen & Baddeley, in press; Page & Norris, in press) in which articulatory suppression and IS have been shown to behave in quite different ways. Most significantly, AS abolishes the phonological similarity effect for visual presentation, whereas IS does not (e.g., Larsen & Baddeley, in press). Because this issue has been dealt with in such detail in these papers, we will not discuss it further here.

Neath has recently extended Nairne's (1990) feature model to account for IS effects (Neath, 2000). In common with the O-OER model, the feature model accounts for the effects of both IS and articulatory suppression in largely the same way. In the feature model both articulatory suppression and IS are seen as adding noise to modality-independent features of the items being remembered, via a process described as "feature adoption". Again, a detailed discussion of whether or not IS and articulatory suppression are equivalent is outside of the focus of this paper. In this paper we will concentrate on the conditions under which each of the models predicts retroactive effects of IS.

The work reported here was prompted in part by a third perspective on the effect of IS. Cowan (1995) suggested that the effect has an attentional origin and that dealing with the irrelevant sound may compete with resources required for retention. In accord with this, Elliott (2002) concluded that developmental changes in the effects of IS were attributable to attentional demands. Note that the fact that the IS effect with visual presentation is abolished by articulatory suppression (Hanley, 1997; Salamé & Baddeley, 1982) is inconsistent with a general attentional account. If the IS effect is attentional, it must apply specifically to the attentional demands of maintaining information in the phonological store. The idea that there might be an attentional component to the IS effect would be

consistent with other data showing that increases in processing demands can have an effect on the retention of information already in STM and, moreover, that this effect can be retroactive (Rabbit, 1968; Posner and Rossman, 1965; Luce, Feustel & Pisoni, 1983). This raises the possibility that IS might also be able to exert a retroactive effect. That is, contrary to the claims of theories such as Jones's O-OER model (Jones, 1993; Macken and Jones, 1995) and Nairne's feature model (Nairne, 1990; Neath, 2000), there may be no need for the IS to be presented at the same time as the items to be remembered for the manipulation to have an effect. As we will explain later, if IS were found to have such a retroactive effect, this would pose considerable difficulties for these theories.

Retroactive effects of IS with visually presented lists have been reported by Miles et al. (1991), Macken and Jones (1995), Beaman and Jones (1998) and Macken, Mosdell and Jones (1999). In the former two studies IS could be presented during a 10-second retention interval following a visually presented list. Note that Hanley and Bakopoulou, 2003, found a retroactive effect with auditorily presented lists though their result is somewhat open to the interpretation that IS presented after an auditory list might interfere with acoustic/phonetic memory. However, the exact implication of the data from visually presented lists depends critically on whether or not participants were able to rehearse during the retention interval, simultaneous with the presentation of the IS. According to Jones and colleagues, these retroactive effects must arise because the IS is presented while participants are rehearsing the list. That is, although there is no IS when the list is originally presented, there is IS when the list is re-presented by rehearsal. Their commitment to this view is clear from statements made in a number of their papers. In discussing the locus of the IS effect, Beaman and Jones (1997) claim that their

"changing-state hypothesis suggests that order information is lost during the maintenance rehearsal stage of processing" (p. 468). Similarly, Beaman and Jones (1998) state that "the prediction [that IS during the list and during retention are equivalent] is based on the assumption that rehearsal would be undertaken continuously throughout the retention interval" (p.626) and Macken et al. (1999) propose that "speech will interfere with recall to the extent that it is presented when the burden on rehearsal is relatively great" (p.811). These statements imply that, when rehearsal is prevented, there should be no retroactive effect of IS presented during a retention interval.

The claim that rehearsal, or even maintenance of serial order, is important in generating an IS effect has been challenged by LeCompte (1996). LeCompte demonstrated an IS effect in a missing-digit task, claiming that the missing digit task involves neither maintenance of serial order nor subvocal rehearsal. Jones and Macken (1993) and Macken and Jones (1995) have also argued that the missing digit task does not involve serial rehearsal. However, although the missing digit task could, in principle, be performed without either rehearsal or regard for serial order, LeCompte acknowledges that there is no independent evidence that this is so in practice. Indeed, one obvious strategy for performing this task is to maintain ordered subgroups of incoming digits so that new digits can be readily added to their appropriate place. This strategy involves both coding serial order to maintain the subgroups and a rehearsal-like process to update the groups.

LeCompte offers an explanation of the IS effect in terms of temporal distinctiveness theory (TDT) (Glenberg & Swanson, 1986; Glenberg, 1987). His basic account assumes that the IS occupies the same temporally defined search space as the to-be-remembered

list items, and that this overloads the retrieval process. This explanation has to predict that if IS is presented after the list items, so as not to occupy the same temporal search space, there should be no adverse effects of the irrelevant material. Recent experimental evidence against LeCompte's version of TDT comes from Macken et al. (1999). They presented IS either in the 5s before list presentation, the first 5s of presentation, the last 5s of presentation, the first 5s of retention or the last 5s of retention. They argued that the TDT explanation of the IS effect in terms of interference with the temporal search set predicts that IS presented immediately before the list should impair performance even more than IS presented 5-10 s after presentation, especially for early list items. However, IS presented before the list had no effect whereas there was a significant effect of IS presented after the list and of IS presented during the second half of the list. Once again, the most obvious way to make LeCompte's account at least partly consistent with these data would be to assume that the IS and list items do occupy the same search space during subvocal rehearsal that follows list presentation.

A retroactive effect of IS would also present difficulties for Neath's (2000) modifications to the feature model. In the feature model IS operates by adding noise to the features of the items being remembered by means of a process of "feature adoption". Feature adoption should take place only when the IS is simultaneous with either the list items or their rehearsal. (Note: if this were not the case then there would appear to be nothing to prevent feature adoption between list items themselves.) This is certainly the interpretation of the feature model given by Surprenant, LeCompte and Neath (2000) who state:

“One weakness of the feature model is that... it cannot simulate the detrimental results of IS when the IS occurs after presentation but before recall... However, it can offer an explanation. During this interval, subjects are explicitly asked to rehearse the items silently. Thus, there is still contemporaneous presentation of the irrelevant information and the to-be-remembered items. (p.345)”

and by Neath (2000), who goes on to say that "If this account is correct it follows that the IS effect should be eliminated if rehearsal in this type of setting is prevented" (Neath, 2000, p.420).

All three of these models (O-OER, feature theory, TDT) therefore predict that there should be no retroactive effect of IS in the absence of rehearsal. However, in all existing demonstrations of a retroactive IS effect, it is possible that participants may have been able to rehearse during the retention interval. For example, in the Miles et al. (1991) study there was an effect of IS presented during a 10 second retention interval. Although they did have a condition where participants were required to suppress (repetition of 'the') during the delay, they did not report whether the IS effect was reliable under suppression. In the study by Macken et al. (1999), the retention interval was unfilled, clearly allowing participants to rehearse the list throughout.

The strongest data supporting a retroactive effect of IS at a time at which rehearsal is prevented comes from Macken and Jones (1995), though they did not draw attention to this particular aspect of their results. In several experiments they examined the effects of different kinds of suppression during a retention interval. They contrasted steady-state suppression, in the form of mouthed (silent) repetition of the letter A, with changing-state

suppression in the form of repetition of the letters A-G. In their fifth experiment, they found that changing-state but not steady-state suppression reduced the size of an IS effect, but the effect was not abolished by either form of suppression. This suggests that neither concurrent presentation nor concurrent rehearsal is necessary to obtain a retroactive effect of IS. However, as the quotations from papers by Jones and colleagues presented above indicate, they still maintain that the IS effect is mediated by its effect on rehearsal. In their defence, it could be argued that mouthed repetition of the letters A-G was not actually sufficient to simply eliminate rehearsal. Indeed, the primary aim of their study was to demonstrate that changing-state suppression (repetition of the letters A-G) harmed memory more than steady-state suppression (repetition of the single letter A). There was therefore no reason for them to use a more taxing suppression task that could have been guaranteed to block rehearsal.

LeCompte's TDT, Nairne and Neath's feature model and Jones's O-OER theory all predict that any retroactive effect of IS depends on rehearsal. The other competing explanation of the IS effect is that supplied by the WM model. However, this model is rather underspecified in that it makes no direct prediction about the point in time when IS can influence the phonological store. The only critical prediction from the WM model is that IS effects should depend on information being retained in the phonological store.

The possible existence of a retroactive effect of IS in the absence of rehearsal therefore provides an opportunity to assess these competing models and may indicate ways in which the WM model should be extended. In the experiments that follow, we examine retroactive effects of IS under conditions designed to minimize the possibility of rehearsal.

Experiment 1

Introduction

In all of the experiments reported here, we attempted to prevent participants from rehearsing during a retention interval by engaging them in another task throughout. In all but one of these experiments, IS is presented during this filled retention interval. Because we were initially worried that preventing rehearsal by having participants read aloud visually-presented items might produce its own IS effect, thus swamping any effect of our deliberate IS manipulation, we began by using an arithmetic task that could be performed in silence. Participants were presented with lists of four letters, followed by three single digits, in turn followed by an equals sign. The letter, digits and the equals sign were all presented singly at a rate of one every 750ms. When the equals sign appeared, the participants' task was to write down the sum of the three digits in a response box, before recalling the list of four letters. IS was either absent altogether or could be present either during the letter-list presentation, or during the digit/equals-sign presentation, or during both.

Method

Participants

The participants were 16 students from the University of Bristol who were paid for their participation. In this, and all of the experiments reported here, participants were all native speakers of English.

Materials

Sixteen participants were presented with lists of 4 letters drawn randomly from the set B, H, J, L, Q, R, X, Z, with no letter repeated in a given list. The letters were followed by three single digits drawn from the set 1, 2 and 3, and then by an equals sign. The digits were randomly chosen with the constraint that no digit appeared twice in succession. Each item was presented visually, in the centre of a computer screen placed approximately 40 cm from the participant. Items were displayed in black on a white background, and the letters and digits were approximately 1 cm high. All items, including the equals sign, were presented at a rate of one every 750ms. Items were displayed for 650 ms followed by a blank period of 100 ms. One hundred ms after the equals sign disappeared, the word "Recall" appeared on the screen. Each participant saw 120 trials with no list repeated. The lists were generated so as to avoid any alphabetic runs (e.g. QR). No letter appeared in the same position as it had done in either of the two preceding lists and no letter triple appeared in two consecutive lists. The eight letters in the experimental set were approximately balanced, in terms of frequency of use, across the four serial positions. Eight practice lists were generated under the same constraints.

During a trial, participants might hear excerpts of Finnish speech, played at a comfortable volume, through headphones. (Colle, 1980, and Ellermeier and Hellbrück, 1998, have shown that the IS effect is largely independent of the loudness of the speech.) The Finnish speech had been recorded onto a DAT recorder by a female native Finnish speaker reading from a novel. The recordings had then been transferred digitally to a computer and converted to 11.025 KHz sampling rate with 16 bit resolution. The speech was edited into sections of continuous speech 3s or 6s in length. Where necessary,

pauses in the speech were edited out so that the speech sounded fluent and continuous to non-Finnish listeners. Each section of speech was used only once for each participant.

There were four IS conditions: in one condition participants heard no speech during the trial (no IS); in a second condition they heard three seconds of speech that started 50ms before the visual presentation of the first letter and ended 50ms before the onset of the first digit (IS during list); in a third condition participants heard three seconds of speech that started 50ms before the onset of the first digit and continued until 50ms before the word "Recall" (IS during sum); in the fourth condition, participants heard six seconds of speech that started 50ms before the first letter and continued until 50ms before the recall cue (IS throughout). The four conditions were distributed equally and randomly around the 120 lists resulting in 30 lists per IS condition. The 16 participants were divided into four groups of four, each group seeing a different allocation of lists to IS conditions.

Procedure

Participants were instructed to view the letters and digits in silence. When the equals sign appeared they were to write down the sum of the three digits and then to recall the letters in order in the response boxes provided. Participants were instructed to be as accurate as possible in calculating the sum of the digits. They were told that the digits would always be drawn from the digits 1, 2 and 3 and that the sum would, therefore, always be less than 10. They were informed that their letter recall on any given trial would only be marked if their answer to the sum calculation was correct; for this reason they were instructed not to try to rehearse the letter sequence during digit presentation as this would be likely to interfere with their arithmetic task. The particular form of the arithmetic task was selected following informal experimentation that suggested that

participants would not be able to rehearse the letters while performing the task accurately. Eight practice trials (two from each IS condition) were presented and participants had an opportunity to ask the experimenter to clarify any points about which they were still unsure. Participants initiated presentation of each list by pressing the spacebar, and could therefore pause briefly between lists if they wished. After 60 lists they were invited to rest for a short time if they felt it necessary.

Results

The mean percentages of items correct for the four IS conditions are shown in Table . To be marked as correct an item had to appear in the correct recall position, a criterion that applies to all the experiments reported here. These figures are based on lists for which participants responded with the correct digit-sum, comprising 90% of lists presented. This percentage did not vary significantly with condition (means: IS on list 91%; IS on arithmetic 90%; IS throughout 89%; no IS 90%) and, in particular, there was no indication of an IS effect on the rate of arithmetic errors, $t(15)=0.77$, $p=.45$. We also analyzed the data using a lax criterion, where the lists were scored regardless of whether the arithmetic task was correct; this made no difference to the pattern of results reported below. (There were not sufficient data to enable meaningful analysis of lists for which the arithmetic was incorrect.) There is a large effect of IS on recall when the IS is presented throughout the trial, and this effect is approximately halved when the IS is presented simultaneous with either the letters or the digits. To confirm this interpretation, we ran a four (IS) by four (serial position) repeated measures ANOVA. This analysis revealed statistically significant effects of IS condition, $F(3,36)=8.14$, $p<.001$, and serial position $F(3,36)=14.40$, $p<.0001$, with no significant interaction between the two, $F(9,$

108)=1.44, $p=.18$. (Effects of serial position are found throughout this paper, and reflect entirely standard serial position curves; for this reason, and to avoid complicating the presentation of the results, we will not report the means for each serial position.) To test the more specific pattern of results across conditions we conducted planned comparisons on the means for the IS conditions averaged across serial position. This revealed that performance with no IS was reliably better than that on any of the IS conditions (all $p_s < .05$); that performance on the IS during list and IS during sum conditions did not differ reliably, $p=.69$; that there was a reliable difference between IS during sum and IS throughout, $p=.021$; and that there was a suggestion of a difference between the IS during list and IS throughout conditions, $p=.056$.

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Discussion

The results of Experiment 1 demonstrate that there is a retroactive effect of IS. Furthermore, IS presented after the end of the list to be recalled, but before the recall itself, has approximately the same effect as the same amount of IS presented simultaneous with the list. Given the constraints placed on the participants by the requirement to perform the arithmetic task (correctly) during the retention interval, we think it unlikely that this retroactive effect of IS can be explained by assuming that participants were rehearsing during this interval. We can, of course, never be completely certain that a covert task has prevented rehearsal, so it is perhaps better to view the results

of Experiment 1 as indicative rather than definitive. At the very least, we can claim with some confidence that the opportunities for rehearsal during the retention interval are much reduced relative to those during list presentation. This has no effect on the size of the IS effect observed. In the experiments that follow we build on this result by showing that a retroactive effect of IS persists even when we use an overt speeded digit-reading task to prevent rehearsal.

Experiment 2

Introduction

In the next experiment we once again examined the retroactive effect of IS. In addition, we investigated the timecourse of this effect. In particular we wished to compare the effect over short retention intervals where recall is likely to be supported by the phonological store, with longer intervals for which the store is unlikely to be involved, at least at retrieval. It is difficult to extend the arithmetic task used in Experiment 1 without making the task much harder as retention interval increases. All of the remaining experiments reported here, therefore, used an overt digit-reading task (as did e.g., Bjork & Healy, 1974; Nairne & Kelley, 1999) to prevent rehearsal during a retention interval. Participants were required to read aloud a sequence of digits presented singly on a computer display screen. Although this involves overt speech that might itself be expected to constitute IS, we should note that the articulatory component of reading should not itself eliminate the IS effect. Even in their changing-state mouthed-suppression condition, Macken and Jones (1995) found a significant IS effect with suppression during a 10s retention interval. Although the standard procedure used to prevent rehearsal is articulatory suppression, the rate and difficulty of the suppression

task varies widely, and it is sometimes difficult to ensure that participants comply with instructions. Moreover, articulatory suppression is most often used to prevent rehearsal during list presentation, whereas here we are more interested in preventing rehearsal in a subsequent, and otherwise unfilled, retention interval. In contrast to standard suppression, the digit reading task enables the rate of speaking to be controlled, and the unpredictability of the digits makes it unlikely that participants are able to automatize the process.

In Experiments 2, 3 and 4, we presented participants with digits at the rate of one every 750ms. In pilot work participants reported being unable to rehearse at this rate, and some found faster rates of presentation impossible to keep up with. Note that Beaman and Jones (1997), in their study of IS, considered that articulatory suppression consisting of repeating the letters A-G at a rate of one letter per second was sufficient to prevent rehearsal. Digit reading at one digit per 750ms is a much harder task. In our final experiment we present data collected with a reading rate of one digit every 500ms. This is twice the rate of articulation (and with a more difficult task) that Beaman and Jones assumed would prevent rehearsal. As will be seen, the data give a consistent picture across manipulations of the reading rate.

Much previous work has suggested that the contribution of phonological short-term memory to the serial recall task is short-lived, perhaps being lost after as little as 3 seconds of rehearsal-free delay (e.g. Baddeley & Scott, 1971; Bjork & Healy, 1974; Conrad, 1967; Estes, 1973; Houston, 1965; Muter, 1980; Peterson & Johnson, 1971; Tehan & Humphreys, 1995). We expected the retroactive IS effect to have its effect predominantly on the phonological store itself. If so, the effect of IS should decrease with

increasing retention intervals as retrieval from the phonological store becomes less likely. Colle and Welsh (1976) found only a small (3%) and unreliable effect of IS even after 30s of backward counting, a retention interval presumably sufficient to abolish the use of the phonological store at retrieval. However, as noted earlier, other studies have emphasized the dependence of the IS effect on encoding within the phonological store (Hanley, 1997; Salamé and Baddeley, 1982) .

Experiment 2 was designed to examine the timecourse of the IS effect and to confirm the retroactive effect using an overt digit-reading task, rather than a covert arithmetic task, to prevent rehearsal. The contribution of the phonological store to memory performance was indexed by tracking changes in a phonological similarity (PS) effect over time. Poorer performance on phonologically confusable than on nonconfusable items is the classic indicator of involvement of the phonological store in short-term recall. As indexed by the PS effect, the phonological store generally decays over a period of 3-6s (Bjork & Healy, 1974). In Experiment 2 we included six confusable letters in the 12-letter stimulus set and tested recall after periods of 3, 9 and 12s.

Method

Participants

The participants were 30 students from the University of Cambridge who were paid for their participation.

Materials

Participants saw lists of 4 letters, presented in the same manner and in the same timing as in Experiment 1. On a given trial, the list comprised an ordering of either the set BDPY (3 phonologically confusable, 1 nonconfusable) or the set FSXQ (ditto) or the set

HRJZ (4 nonconfusable), with these three sets being presented in rotation. All lists contained at least one nonconfusable item, so that there would be a within-list measure of phonological confusability. Note that previous experiments (Baddeley, 1968; Bjork & Healy, 1974; Henson et al., 1996) have shown that performance on nonconfusable items in a list is unaffected by the presence of confusable items in that list. The ratio of 2 lists of mixed confusability to one pure nonconfusable list then resulted in equal numbers of confusable and nonconfusable items. Of the 12 letters used in this experiment, therefore, 6 were confusable and 6 nonconfusable. For a letter in a given set there was no letter in either of the other two sets with which it was phonologically confusable. Constructing the materials in this way permitted us to maximise our chance of observing a PSE, by including three rhyming letters in each mixed list, at the same time as balancing the occurrence of confusables and nonconfusables across conditions and serial positions. There are 24 possible orderings of each of the three letter-sets. To give good experimental power participants saw each letter combination twice, giving a total of 144 lists. A given list was presented once in each half of the experiment with at least 36 lists intervening between its first and second presentations. All experimental manipulations were completely balanced across the first and second halves of the experiment.

Procedure

On a given trial participants were asked to read the letter list in silence. 100 ms after the disappearance of the final letter (i.e. 750 ms after the final letter's onset) the word "loud" appeared on the screen and participants were required to read it aloud. The word "loud" was selected so as to remind participants to switch from silent reading to reading aloud at this point in the trial. Like the letters, the word remained on screen for 650 ms, followed

by 100 ms of blank screen. There followed a number of individual digits that subjects were required to read aloud. These appeared at a rate of one digit every 750 ms. As with the letters, each digit appeared on the screen for 650 ms with the screen blank for the remaining 100 ms of the digit inter-onset-interval. This rate of digit reading was taken to be sufficient to prevent subvocal rehearsal and the quality of reading was monitored by the experimenter to ensure compliance. The digits were taken from the set 1, 2, 4 and 6, comprising digits with single-syllable names sharing minimal phonology with the experimental letters. They were generated in random order with the constraint that no digit appeared twice consecutively. After the experimentally manipulated number of digits had been read aloud, the word "Recall" appeared and participants were required to write the letter list in order (instructions as before) in the response boxes provided. Digit reading allowed us to control the retention interval on a trial-by-trial basis as a within-participant factor. In this experiment we used 3, 11 and 15 digits that, together with the word "loud", resulted in retention intervals (measured from the onset of the word "loud" to the onset of the recall cue) of 3, 9 and 12 seconds respectively. We chose these retention intervals because the phonological loop might be still in use at 3 seconds, but not at 9 and 12 seconds. Moreover, we wished to compare performance at 9 and 12 seconds in order to see whether an asymptote in performance was being approached at these comparatively long retention intervals.

The presence of IS was also manipulated within participants. On half the trials the first 3 seconds of the retention interval was accompanied by three seconds of IS presented over headphones in the same way as in Experiment 1. The IS stimuli were the same as those employed in earlier experiments and participants were asked to ignore the IS as best

they could. On the other half of trials, participants heard white noise during the first 3 seconds of the retention interval. The white noise was of constant amplitude and the level was adjusted so as to match the subjective loudness of the IS stimuli. White noise has been shown to have no effect on serial recall performance of visual material (Colle & Welsh 1976; Salamé and Baddeley, 1987) and was included here to control against the possibility that the onset of the to-be-ignored stimulus might have some unexpected attentional consequences.

With three levels of retention interval crossed with two levels of IS, each participant experienced lists in six experimental conditions. These six conditions were seen in a random order. Because any given letter appeared six times in each serial position in each half of the experiment, it was possible to ensure that each of these occurrences was seen in a different condition. We divided the 30 participants into 6 groups of 5 and each subject-group saw a different random allocation of lists to conditions.

On the basis of the standard WM model, we predicted that the effects of both phonological similarity and irrelevant sound would diminish with increasing retention interval.

Results

The experimental data were subjected to a two (IS) by two (confusability) by three (delay) by four (serial position) repeated measures ANOVA. The values for the mean percentage of items correct, collapsed across serial position, are given in Table 2.

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There were main effects of IS, $F(1,24)=13.6$, $p=.001$, delay, $F(2,48)=49.4$, $p<.0001$, and serial position, $F(3,72)=62.2$, $p<.0001$, but no main effect of confusability, $F(1,24)=2.6$, $p=.12$. None of the interactions between these factors approached statistical significance. In particular, the potentially interesting interaction between IS and delay was not reliable ($F<1$). Performance declines rapidly, even over these fairly short filled retention intervals, appearing to reach something of an asymptote at the two longer intervals (9 and 12 seconds). Note that this asymptote is still well above chance levels of performance which can be no more than 25% correct. A small but reliable effect of IS is present even at the longer delays, as was confirmed by planned contrasts at the 9 and 12 second delays, that gave $t(29)=2.4$, $p=.012$, and $t(29)=1.8$, $p=.039$, both one-tailed.

Discussion

Even though participants were engaged in reading digits aloud at a rapid rate throughout the duration of the IS, Experiment 2 still produced a reliable retroactive IS effect. Neither the articulatory, nor the overt speech components of the reading task were sufficient to eliminate the IS effect. More surprising, at least from the point of view of the WM framework, is the finding that the IS effect persists even at the longer delays used. The WM model suggests that PS and IS both affect serial recall performance by the effect that they have on the phonological loop component of WM. The phonological loop comprises a phonological store that is extremely labile, decaying in a matter of seconds if not refreshed by an articulatory control process implementing rehearsal. The results of this experiment suggest that even after as little as 3 seconds of filled (i.e. unrehearsed)

delay, there is too little influence of the phonological loop to give rise to a significantly detrimental effect of PS. However, despite this presumed absence (or very weak presence) of phonological loop involvement at retrieval, the IS effect persists even at the longer delays. This suggests either that the phonological loop is not the locus of the IS effect, or that IS affects both the phonological loop and whatever alternative system is used at long delays. Note that we can be sure that the failure to observe a PS effect in this experiment was not due to any problems with the materials. In an unpublished study using exactly the same materials and procedure, but with retention intervals of only 0.75 or 1.5 seconds, we have found strong effects of both PS and IS.

We should perhaps not be too surprised to find effects of IS outliving the effective contribution of phonological short-term memory. As noted earlier, Colle and Welsh (1976) found a numerically similar (3%) effect of IS even after 30s of backward counting, although their effect was not statistically reliable. Beaman and Jones (1998) examined the effect of IS in a free-recall task. They showed that most of the effect is concentrated in those parts of participants' recall that show the biggest influence of serial encoding. They argue that IS has its effect on memory for order in particular, and that when such memory is used in the less constrained free-recall task, the effect of IS will appear to affect free recall performance. For our purposes, we should simply note that any memory for order found in an experimental task like Beaman and Jones's, involving free-recall of 16 item lists, is unlikely to stem from direct involvement of the fast-decaying phonological loop. Thus it may be that IS has its effect on memory for order, whether that memory is implemented by the phonological loop or by some alternative store.

Although the primary motivation for Experiment 2 was to demonstrate a retroactive effect of IS, it also revealed that the IS effect can be detected after as much as 12 seconds. There was no indication of a PS effect at all in this experiment and the overall level of performance is well below that associated with the use of the phonological store. This makes it unlikely that the IS effect results from retrieval from the store itself. This presents something of a conundrum for WM theorists: if the IS effect is dependent on use of the phonological store, then why is it still seen when retrieval from the store is not indicated. In the next experiment, therefore, we attempted to establish the reliability of this long-lasting IS effect. One problematic aspect of Experiment 2, at least from the perspective of establishing the relationship between the long-lasting effect and the phonological store, is that we found no effect of PS, even at the shortest delay. As we have pointed out, this is not due to any problem with the materials themselves, as PS effects can be found with these materials when only short delays are used. In Experiment 3, therefore, we included an even shorter delay of 0.75s, along with delays of 3s and 12s. Because of this short delay we could not use retroactive IS for this experiment and used the more standard procedure in which IS is presented simultaneous with list presentation. This is the only experiment for which such simultaneous presentation was used.

Experiment 3

Introduction

In Experiment 2 we showed that there was a retroactive effect of IS even when retention intervals were long enough to abolish the PS effect. In Experiment 3, we wished to replicate the finding of a long-lasting IS effect in a study in which the presence of one condition with a very short retention interval should encourage use of the phonological

loop, at least at the encoding stage. In this way, we hoped to chart the differing timecourses of the PS effect and the IS effect (hypothesized to be short- and long-lasting respectively) in a single experiment using the same materials.

In this experiment we once again manipulated the length of a filled retention interval. As above, participants were asked to read aloud the word "loud" followed by digits appearing at a rate of one every 750ms. The three retention intervals used 0, 3 and 15 digits giving retention intervals of 0.75s, 3s and 12s respectively. Retention interval changed randomly from one list to the next, there being an equal number of each overall. Each list was accompanied by 3s of either IS (Finnish) or white noise, again balanced within participant. IS was simultaneous with list presentation in this experiment owing to the requirements of the 0.75s retention interval.

Method

Participants

Participants were 36 members of the the MRC CBU subject panel aged 17--38 yrs, who were paid for their participation.

Materials

The IS and white noise materials were the same as those used in the two previous experiments. A reviewer of an earlier version of the paper expressed a concern that because Y can represent a vowel (although the letter name itself is not pronounced as a vowel) this might have facilitated recall of lists in which it was present. The letter Y in the set BDPY was therefore replaced by the letter L. We originally chose the letter Y to ensure that that no letter in a given set was phonologically similar to any in another letter set; L shares a vowel sound with the letters F, S and X. In total there were 144 lists,

generated in the same way as for Experiment 2, this time using the letters sets BDPL, FSXQ and HRJZ.

Procedure

The procedure on each trial was the same as that used in Experiment 2, with only a change to the durations of the retention intervals and the placement of the IS. There were six conditions, comprising a crossing of three retention intervals with the IS/white-noise manipulation. The 36 participants were divided into six groups, such that participants in a given group saw a different mapping of condition to list from those in other groups.

Results

The means for the various conditions are shown in Table 3. Results were analyzed using a two (IS) by two (confusability) by three (retention interval) by four (serial positions) repeated measures ANOVA. Note that "confusability" refers here, and always, to items not lists. The single nonconfusable items that appeared in lists with 3 confusable items are treated as nonconfusable in this analysis. This revealed main effects of IS, $F(1,30)=16.5$, $p < .001$, with worse performance for IS than for noise, of retention interval, $F(2,60)=98.7$, $p < .001$, with worse performance for longer retention intervals, and an effect of serial position, $F(3,90)=87.9$, $p < .001$, consistent with standard serial position curves. As in Experiment 2, the effect of IS was significant even at the 12s delay, $t(35)=2.0$, $p=.027$, one-tailed. There was no main effect of confusability, $F(1,30)=2.4$, $p=.13$. The theoretically interesting interactions of IS with delay, $F(2,60)=1.2$, $p=.32$, and IS with phonological confusability, $F(1,30)<1$, $p=.88$, did not approach statistical significance. The only significant interaction was between confusability and delay, $F(2,60)=6.0$, $p=.004$, indicating that the disruptive effect of

phonological confusability decreased with increased retention interval. Planned comparisons showed that the effect of PS was significant only at the 0.75s retention interval, $t(35)=3.3$, $p=.002$. Once again there was a small but unreliable advantage for phonologically confusable letters at the longest retention interval.

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Insert Table 3 about here

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These results support the idea that there is phonological encoding on all trials; participants were unaware, at the encoding stage, of the length of the upcoming retention interval. Moreover, they suggest that retrieval from the phonological store is only feasible at the shortest retention interval. Nonetheless, the IS effect shows no such interaction with delay.

Discussion

Consistent with Experiment 2, Experiment 3 demonstrated a significant effect of IS that persisted even after retention intervals at which the PS effect is abolished. The absolute size of the IS effect is approximately constant across retention intervals. However, when measured as a proportion of the number of errors at each retention interval, the effect of IS is greater for the shorter intervals (0.16 and 0.17 for the 0.75s and 3s retention intervals respectively) than it is for the 12s retention interval (0.06).

There is an effect of confusability at short retention intervals that disappears as the retention interval increases. To reiterate, because participants had no idea at the start of a given trial how long the retention interval would be, the abolition of a PS effect by retention intervals as short as 3s cannot be attributed to a difference in the initial

encoding process. It seems, therefore, that the effects of PS and of IS really do have different timecourses in the context of a single experiment in which phonological encoding can be presumed to be carried out for all lists. This result is somewhat unexpected from a classical WM perspective, and will be discussed further in relation to the next experiment.

Finally, we should note that replacement of the letter Y with the letter L in one of the letter sets made little difference to the general pattern of results.

Experiment 4

Introduction

In Experiments 2 and 3 we have shown an effect of IS that persists even after retention intervals sufficient to abolish the PS effect. Does this mean that the IS effect is dependent on some storage system other than the phonological loop, a result which runs counter to previous findings noted above? Or is it perhaps sufficient for an effect of IS that the list has at some point entered the phonological store, whether or not that store is subsequently used at retrieval. In our next experiment we addressed this question directly. Is a long-lasting effect of IS contingent on the stimulus list having at some time been in the phonological store?

One way of examining whether the long-lasting effect of IS seen in previous experiments was mediated by the effect of IS on the phonological store, is to look at the retroactive effect of IS when combined with articulatory suppression during list presentation. Articulatory suppression during list presentation should prevent visual information from being recoded into the phonological store. This would force participants to rely on some alternative store for their recall attempt. If IS influences information in

this alternative store directly, then there should still be a retroactive IS effect with suppression at input. If the effect of IS is always mediated by the phonological store, then articulatory suppression at input should prevent access to the store and eliminate the retroactive effect completely. Using simultaneous presentation of IS with visual presentation and immediate recall, Salamé and Baddeley (1982) and Hanley (1997) found that articulatory suppression completely eliminated the effect of IS. This seems to support the idea that there is no effect of IS without involvement of the phonological store. However, in these experiments it is possible that suppression during input only eliminates the effect of simultaneously presented IS. Experiment 4 therefore examines the effect of articulatory suppression at input on the retroactive IS effect.

Participants

The participants were 32 members of the Cognition and Brain Sciences Unit subject panel aged between 16 and 40 years, who were paid a small fee for their participation in the experiment. None had taken part in any of the previous experiments.

Materials, Design and Procedure

The lists were identical to those seen in Experiment 2¹, the total letter set comprising six confusable letters and six nonconfusable. The four-letter lists were presented at a rate of one item every 750ms, comprising a 650ms presentation of the letter followed for 100ms by a blank screen. The letters were followed, in the same rhythm, by the word "loud" followed by 11 digits selected as in the previous experiments. These twelve items therefore lasted 9 seconds. Participants were required to view the letters then to read aloud the word "loud" and the subsequent digits. In half the trials, participants were additionally required to perform articulatory suppression during presentation of the

letters. This comprised repeatedly saying the word "racket" at a rate of approximately twice per second. Because the lists were presented visually, it was expected that articulatory suppression during input would prevent any verbal recoding of the letters, thus denying them access to the phonological loop component of short-term memory. To avoid adding too much complication to an already complex task, articulatory suppression was blocked, with half the participants suppressing for the first block of 72 trials, the remaining subjects suppressing for the second 72 trials. In a random half of the trials, participants heard 6 seconds of irrelevant Finnish speech located centrally in the 9-second retention interval. In the other half, white noise matched in root mean squared amplitude was played at the same point in the trial. As before, subjects were instructed to ignore the IS and white noise. There were two different mappings of lists to IS conditions, each seen by half the subjects. Crossing these mappings with the blocking of articulatory suppression produced four groups of subjects. All experimental manipulations were completely balanced by list position and by experimental block. There were six practice trials before the first block and four before the second block with a short break between blocks. The practice trials comprised combinations of the letters GKLN and included an equal number of each IS condition.

Results

The experimental data were subjected to a repeated-measures ANOVA with four within-participant factors: confusability, suppression and IS, each with two levels, and serial position, with four levels. Neither of the between-participant factors, list or block order, had a reliable effect on performance.

The means for the various conditions, collapsed across serial position, are shown in Table 4. There were main effects of IS $F(1,28)=4.4$, $p<.046$, suppression $F(1,28)=19.1$, $p<.001$, confusibility $F(1,28)=4.529$, $p<.042$, and serial position, $F(3,84)=27.5$, $p<.001$. The main effect of IS was in the expected direction with worse performance for speech than for noise. Performance was also worse under suppression. Confusable letters were actually recalled slightly better than nonconfusable letters, a reversal of the pattern associated with use of the phonological loop. This reversal was present, but not reliably so, in Experiments 2 and 3 above. It accords with the findings of Nairne and Kelley (1999) who also found that the PS effect could reverse after long filled retention intervals. Tehan, Hendry and Kocinski (2001) have supplied evidence that such reversals stem from better item recall in the similar condition. According to both sets of authors, the shared rhyme in similar lists provides a cue that helps subjects guess the items, while providing no information about item position.

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Insert Table 4 about here

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The primary motivation for Experiment 4 was to determine whether the IS effect at long retention intervals would be abolished by suppression at input. One prediction of the WM model is that an effect of IS should be present only following initial storage in the phonological loop, that is, in the no suppression condition. Planned comparisons revealed that with no suppression there was indeed a reliable effect of IS, $t(31)=2.71$, $p=.012$, that disappeared with suppression, $t(31)=0.14$, $p=.90$. In fact, under suppression the error rates for the IS and no IS conditions are almost identical. To test whether the IS effect was

reliably larger in the no-suppression condition, we performed a one-tailed t-test (the direction of the prediction being clear) comparing the sizes of the IS effect with and without suppression. As predicted the IS effect was indeed reliably larger in the absence of suppression $t(31)=1.86$, $p=.037$. Note that in a standard analysis of variance the interaction between suppression and IS gives $F(1,28)=3.43$, $p=0.075$. This F-test tests the two-tailed hypothesis asking whether the effect under suppression is smaller or bigger than that found with no suppression. Treating this as a directional test of the specific prediction made here gives $p=0.037$, which is entirely equivalent to the, arguably more familiar, one-tailed t-test.

Discussion

Salamé and Baddeley (1982) and Hanley (1997) both found that there was no IS effect for visually presented lists with articulatory suppression during presentation and recall of the lists. The results of Experiments 1 and 2 indicate that IS can have a retroactive effect, and does not rely on being presented simultaneously with the to-be-remembered items. In line with both these findings, Experiment 4 shows that this retroactive IS effect also disappears when participants must suppress during presentation. Experiment 4 therefore confirms that the effect of IS is specific to the retention of order in the phonological store, and goes further by suggesting that it is encoding in the phonological store that leads to an IS effect, not necessarily retrieval from it. As noted earlier, these data therefore argue against any suggestion that the IS has a general effect on memory for order. Whatever alternative store supports serial recall in the absence of any phonological loop involvement (as in the suppression conditions here), it does not seem to be sensitive to the presence of IS. Note that these results are contrary to the general predictions of the

O-OER model. In describing the O-OER model, Macken and Jones (1995) state that verbal events are represented as "amodal, abstract representations" (p.437) and that "the origin of codes in short-term memory should not be a critical factor in determining disruption of serial recall" (p.437). The data are more consistent with the WM view of short-term memory. Whether or not IS disrupts short-term recall depends critically on whether information is, or has been, held in the phonological store.

Experiment 5

Introduction

One concern that might be raised over the experiments reported so far is that, even with the digit reading task used in Experiments 2, 3 and 4, participants may have been able to perform some rehearsal during the retention interval while the IS was being presented. Two observations lead us to conclude that participants were not rehearsing while performing the speeded reading task during the retention interval. First, there was a catastrophic fall in performance from over 85% correct after 0.75s to approximately 55% correct after 9s or 12s. We know very well that if subjects are allowed to rehearse then they can maintain recall of a four-item list virtually indefinitely. Even a 7-item list can be recalled at 80% correct after an unfilled 10s delay (Jones and Macken, 1995, Experiment 4). If participants are able to rehearse under our conditions, then how can we explain their asymptotically poor performance after 9s? Second, we deliberately included a test of the PS effect in the current series, independent of the IS manipulation. We did this to give us an index of whether participants showed evidence of using phonological short-term memory at retrieval. Consistent with previous research, the PS effect was removed by delays as little as 3s. This is in contrast with Jones and Macken's finding

(Experiment 4) that the PS effect survives a 10s unfilled retention interval in which rehearsal is not prevented, even for a 7-item list. The PS effect even reversed in our Experiment 4, consistent with Nairne and Kelley's (1999) findings.

From these considerations we are confident that, in Experiments 2-4, speeded digit reading has indeed prevented subvocal rehearsal during the retention interval. Clearly, however, it is impossible to prove absolutely that participants were never rehearsing. In the final experiment, therefore, we used an even more demanding digit reading task that pushed participants to their performance limits in order to minimize the possibility that they would have any opportunity to rehearse.

Method

Participants

Participants were 24 members of the MRC Cognition and Brain Science Unit volunteer panel, who were paid for their participation.

Materials, Design and Procedure

In Experiment 5, we used the same 4-item lists as we used in Experiment 3. After each list participants were presented with the word "loud" followed by 11 digits at a rate of one every 500ms. Participants were asked to read both the word "loud" and the digits, as in Experiments 2-4. During the resulting 6-second retention interval participants heard either 6 seconds of Finnish speech or 6 seconds of noise. The reading rate used in this experiment is about the fastest our subjects could manage reliably, and is the same rate as was used, with the same purpose, by Nairne and Kelley (1999). At the end of the experiment all subjects were asked whether they had been able to rehearse any of the

letters while reading the digits. Note that before this, subjects were not informed that the purpose of the digit-reading task was to prevent their rehearsing.

Results

The results of Experiment 5 are shown in Table 5. None of the subjects reported being able to rehearse any of the letters while reading the digits. The data were analyzed using a two (IS) by two (confusability) by four (serial position) repeated-measures ANOVA. There were significant main effects of IS $F(1,23) = 7.5, p = 0.012$, with performance worse with speech than noise, and serial position, $F(3,69) = 35.6, p < .001$. The main effect of PS was borderline significant, $F(1,23) = 4.3, p = 0.05$.

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Insert Table 5 about here

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Discussion

Experiment 5 provides further confirmation of a retroactive IS effect under conditions where we can be as confident as it is possible to be that participants were unable to rehearse. Whatever is the mechanism of the retroactive IS effect, it is not mediated by its influence on rehearsal. Finally, we note that while the effect of retroactive IS is relatively small numerically, it still represents a medium effect size of .55.

General Discussion

Four of the experiments reported here (Experiments 1, 2, 4 and 5) show that IS can have a retroactive effect on the retention of visually presented letters. Experiments 2 and 3 also show that both this retroactive (Experiment 2) and the standard simultaneous effect of IS (Experiment 3), persist at delays of up to 12 seconds. At these delays there is no

indication that participants are retrieving any information from the phonological store. Experiment 4 showed that the retroactive effect behaves just like the simultaneous IS effect in that it only emerges when the to-be-remembered items are first encoded into the phonological store. Experiment 5 confirmed our interpretation of Experiments 2 and 4, by demonstrating as clearly as is possible that the retroactive effect of IS is not dependent on IS being presented while the list is being subvocally rehearsed.

The demonstration of a retroactive effect of IS extends the results of earlier studies by Jones and his colleagues by showing that these retroactive effects are not mediated by any effect of IS on articulatory rehearsal processes. Even when rehearsal is prevented by the requirement to perform an arithmetic task, or the much harder speeded digit reading, IS still has a retroactive effect on the recall of earlier presented material. This result holds even when participants are required to read digits presented at a rate of one every 500ms. This is twice the rate of articulation that Beaman and Jones (1997) considered sufficient to prevent rehearsal in their own study.

These data are inconsistent with the explanations of the IS effect offered by LeCompte's TDT, Nairne and Neath's feature model and Jones' O-OER model. In all of these accounts the IS must be presented simultaneously with the to-be-remembered items, or with their rehearsal, in order to have its effect (see the various quotes to this effect in the introduction). In the case of the feature model, even if it were adapted to allow a genuine retroactive effect of IS, it would still have problems explaining why this effect was abolished in Experiment 4 by articulatory suppression during visual presentation. Experiment 4 confirms earlier results on the effect of suppression on simultaneously presented IS (Salamé and Baddeley, 1982; Hanley, 1997). Both the standard

simultaneous IS effect, and the retroactive effect reported here, depend on the information's having been encoded into the phonological store. Note that any other result would have posed major difficulties for the WM account of IS. According to the WM model, the IS effect takes place in the phonological store. In contrast, the finding that suppression eliminates the IS effect is problematic for the O-OER model which assumes that the representation of serial order in STM is amodal. Even when suppression prevents visual material from being phonologically recoded, subjects still have some memory for order. If information in STM is amodal, then this representation of order should be just as susceptible to interference from IS as is a phonological representation.

Both the retroactive effect of IS, and the standard simultaneous effect persisted even at delays of 9-12 seconds (Experiments 2, 3 and 4). With filled retention intervals of these durations, the phonological store should no longer be contributing to recall. Indeed, there was no sign of the PS effect at this delay. If the IS effect were solely a property of retrieval from the phonological store, then both the IS effect and PS effect should disappear together. This strongly suggests that at least some of the IS effect occurs in whatever store is responsible for recall at these longer delays. Two possibilities present themselves. Either IS influences this longer-term store directly, or it influences the short-term phonological store that then transfers its affected information to longer-term store.

As noted previously, data from Salamé and Baddeley (1982) and Hanley (1997) suggest that there is no IS effect with articulatory suppression at input for visual lists. The standard WM explanation of these results is that suppression prevents information being recoded into the phonological store and participants must rely on one or more alternative stores. Baddeley (2000b) has recently suggested one such store, the episodic buffer,

though other nonexclusive possibilities remain (e.g., a visual store). Given the results of Experiment 4, that showed that the retroactive effects of IS were also eliminated by suppression at input, it would appear that none of these alternative stores is affected by IS. The effect we observe at long delays is most readily attributed, therefore, to transfer of information from the phonological store to a longer-term store that can supplement recall after long, rehearsal-free retention intervals.

Although the present experiments help eliminate several possible explanations of the IS effect, and provide new data on the conditions under which IS effects can be observed, the exact mechanism underlying the effect remains elusive. We have already argued that the findings that the size of the IS effect is not influenced by the PS between IS and list items (Bridges & Jones, 1996; Jones & Macken, 1995; LeCompte and Shaibe, 1997), and that sounds other than speech also interfere with memory (Jones & Macken, 1993; Klatter et al. 1995; Salamé & Baddeley, 1989), argue against a straightforward interference effect whereby IS interferes with the contents of memory by virtue of its perceptual similarity to stored items. Instead we are left with an attentional explanation more like that of Cowan (1995). However, as we noted in the introduction, an attentional explanation must recognize that the IS effect is dependent on the involvement of the phonological store. Page and Norris (in press) have suggested that this dependence results from the fact that IS is a serially ordered, phonological stimulus. As such, it interferes specifically with other serially ordered stimuli in phonological short-term memory. The O-OER model also explains the IS effect in terms of interference between two serially ordered representations. However, the proponents of that model have committed themselves both to an amodal store, and to the requirement that IS is simultaneous with

either presentation or subvocal rehearsal; both commitments are inconsistent with the data we present here. Nevertheless, support for the general view that the IS effect is caused by specific interference between two serially ordered stimuli comes from the finding that changing-state irrelevant stimuli are significantly more disruptive than steady-state irrelevant stimuli (e.g. Jones et al. 1992) --- changing-state stimuli might reasonably be thought of as better examples of serially ordered stimuli than are stimuli that simply comprise the repetition of a single token.

Page and Norris (in press) have presented simulations of IS data from Larsen and Baddeley (in press), using the primacy model. According to Page and Norris, IS has its effect on specific order-representing resources in phonological short-term memory and, hence, on the representation of the to-be-remembered list. In common with the O-OER model, they assume that changing-state IS engages the mechanism responsible for representing serial order. However, the memory impairment arises because the requirement to represent order within two streams (the input list and the IS) depletes the resources available for either. In the primacy model, order is represented by a gradient of activations over localist nodes representing list items. The simulations of the IS effect are based on the simple assumption that the presence of IS depresses, by a common multiple less than unity, the primacy gradient of activations that encodes serial order. In the particular simulations of the IS effect presented in Page and Norris (in press) the data can be accurately fitted simply by multiplying all primacy gradient activations by 0.67 before commencing recall. Page and Norris therefore suggest that the IS effect comes about through a competition for resources between a primacy gradient, representing order in the to-be-remembered list, and another gradient representing order in the irrelevant sound.

This assumption is consistent with the changing-state hypothesis. To the extent that the irrelevant sound does not change state, it should not place demands on a mechanism specifically designed for storing order in short-term memory.

Page and Norris locate the IS effect at the first stage of the primacy model. Although this stage represents order, it does not itself explicitly encode phonological information (see Page and Norris, 1998, for details). Specifically, the primacy gradient representing a list of confusable letters looks no different from that representing a list of nonconfusables, other than being instated across a different set of localist nodes. This would explain why the IS effect is insensitive to the phonological overlap between the to-be-remembered items and the IS. By this account, the IS effect is simultaneously attention and order based. Order (and some item) information is lost because resources are consumed by a competing representation of order. In the context of the retroactive effect described above, it is not important whether the irrelevant sound occurs as the primacy gradient is being formed, or after it has already formed but before recall. In either case, some resources are withdrawn from the primacy gradient representing the to-be-remembered list and are applied to a representation of the order information to be found in the irrelevant stream.

One of the most challenging aspects of the current data, is that the effect of IS remains even at delays where the loop no longer contributes to recall (as witnessed by the lack of a PS effect at these delays). The WM model does not predict this pattern. This is largely because it has not been applied to situations where recall is required after filled delays beyond the duration of the loop. One possibility, however, is that delayed recall depends to some extent on information transferred from STM to LTM. Although the WM model

does not yet give an explicit account of transfer between STM and LTM, it seems plausible to assume that such transfer would be more effective the longer, or more strongly, information is held in STM. If so, the relative duration of the PS and IS effects might be explained in terms of the primacy model. By damping the primacy gradient, IS will cause order to be more weakly represented, and this would reduce the effectiveness of transfer to LTM over the time period, shortly after list presentation, during which such transfer is supposed to occur. In contrast, the PS effect is modelled (Page & Norris, 1998) in terms of confusions in the recall process from the phonological store but, importantly, does not depend on a weakening of the primacy gradient itself. PS should therefore not have any effect beyond the duration of this store. This account is somewhat tentative, but is consistent with the fact that even though we do see reliable and replicable effects of retroactive IS, the effects are numerically quite small.

Although further work is still required to establish the exact nature of the IS effect, the present experiments have placed significant constraints on the set of possible explanations. By demonstrating that there is a retroactive effect of IS, even when the IS is presented at a time when rehearsal is, as far as can be ascertained, impossible, we have been able to question the accounts given by LeCompte's TDT, Jones' O-OER and Nairne and Neath's feature model. We have also shown that articulatory suppression during retention, at least in the form of digit reading, does not prevent IS from interfering with memory. This result provides additional support for the WM view that the reason articulatory suppression eliminates the effect of IS during input of visual lists is because suppression prevents visual material's being phonologically recoded. The effects of both

simultaneous and retroactive IS appear to be on the phonological store and, we hypothesize, whatever system for longer term ordered memory the store affects.

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Footnotes 1

1. Experiment 4 was run before Experiment 3. It is for this reason that Experiment 4 still uses the letter Y as one of the nonconfusables.

Table 1: Mean values of percentage of items correct, collapsed across serial position,
for the conditions of Experiment 1.

Mean (s.e.)	% correct in Exp. 1
No IS	92.0 (2.9)
IS during list	87.4 (4.5)
IS during sum	88.0 (4.3)
IS throughout	84.2 (4.3)

Table 2: Mean values of percentage of items correct, collapsed across serial position, for the conditions of Experiment 2.

Mean (standard error) percent items correctly recalled in Exp. 2					
Retention Interval	Letters	IS condition		IS effect	Conf. effect
		Speech	Noise		
3s	Nonconfusable	67.2 (2.9)	70.3 (2.2)	2.0	0.4
	Confusable	69.1 (2.4)	68.0 (2.0)		
9s	Nonconfusable	55.5 (3.0)	58.0 (2.6)	3.9	-3.7
	Confusable	56.0 (2.5)	61.2 (2.8)		
12s	Nonconfusable	52.6 (2.7)	56.7 (2.5)	2.3	-3.7
	Confusable	58.1 (2.6)	58.6 (2.4)		

Table 3: Mean values of percentage of items correct, collapsed across serial position, for the conditions of Experiment 3.

Mean (standard error) percent items correctly recalled in Exp. 3					
Retention Interval	Letters	IS condition		IS effect	Conf. effect
		Speech	Noise		
0.75s	Nonconfusable	84.3 (2.2)	87.9 (1.7)	2.7	5.5
	Confusable	80.0 (2.3)	81.8 (2.2)		
3s	Nonconfusable	68.3 (3.1)	73.7 (2.9)	5.0	1.7
	Confusable	67.1 (3.2)	71.6 (3.2)		
12s	Nonconfusable	54.6 (3.3)	56.3 (3.3)	2.7	-1.7
	Confusable	55.3 (3.9)	59.0 (3.5)		

Table 4: Mean values of percentage of items correct, collapsed across serial position, for the conditions of Experiment 4.

Mean (standard error) percent items correctly recalled in Exp. 4					
IS condition					
	Letters	Speech	Noise	IS effect	Conf. effect
No suppression	Nonconfusable	60.4 (3.3)	64.6 (3.2)		
	Confusable	61.5 (3.1)	64.5 (2.9)	3.6	-0.5
Suppression	Nonconfusable	51.8 (3.4)	52.6 (3.5)		
	Confusable	56.8 (3.6)	56.3 (3.4)	0.2	-4.4

Table 5: Mean values of percentage of items correct, collapsed across serial position, for the conditions of Experiment 5.

Mean (s.e.) percent items correctly recalled in Exp. 5			
IS condition			
Letters	Speech	Noise	IS effect
Nonconfusable	60.4 (3.5)	64.4 (3.5)	4.0
Confusable	59.2 (3.8)	60.6 (3.7)	1.4
Conf. effect	1.2	3.8	