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

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The authors report 5 serial-recall experiments. In 4 of the 5 experiments, they show that irrelevant sound (IS) has a retroactive effect on material already in memory. In Experiment 1, IS presented during a filled retention interval had a reliable effect on list recall. Four further experiments, 3 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, 2000b; Hanley, 1997; Jones & Macken, 1993; Jones, Madden, & Miles, 1992; Larsen & Baddeley, 2003; Larsen, Baddeley, & Andrade, 2000; 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 (STM) 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 Hanley (1997) and Salamé and Baddeley (1982) found that there was no effect of IS for visually presented lists when participants were required to perform articulatory suppression (AS) 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 that for visual presentation, the effect of IS could be eliminated if AS 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 and 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 et al., 2000; LeCompte & Shaibe, 1997). Almost all of the early IS researchers used speech as the IS; however, a range of ISs 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 Page & Norris (2003), and we return to this in the General Discussion section.

Jones (1993) gives a rather different explanation of the effect of IS in his 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 STM (Jones, Farrand, Stuart, & Morris, 1995). According to this view, serial order is stored in STM in a general workspace regardless of stimulus modality. In addition, Macken and Jones (1995) claim

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that IS should have the same effect on memory as does AS, given that both impair recall by setting up competing streams in memory. The claim that IS and AS have equivalent effects has been challenged in a number of recent articles (Hanley & Bakopoulou, 2003; Larsen & Baddeley, 2003; Larsen et al., 2000; Page & Norris, 2003) in which AS and IS have been shown to behave in quite different ways. Most significantly, AS abolishes the PS effect for visual presentation, whereas IS does not (e.g., Larsen & Baddeley, 2003). Because this issue has been dealt with in such detail in these articles, we do not discuss it further here.

Neath has recently extended Nairne's (1990) feature model to account for IS effects (Neath, 2000). The feature model accounts for the effects of both IS and AS in largely the same way as does the O-OER model. In the feature model, both AS 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 IS and AS are equivalent is outside of the focus of this article. In this article, we 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 IS 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 AS (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 that, moreover, this effect can be retroactive (Luce, Feustel, & Pisoni, 1983; Posner & Rossman, 1965; Rabbitt, 1968). 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 explain in the introduction to this article, 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 Beaman and Jones (1998), Macken and Jones (1995), Macken et al. (1999), and Miles et al. (1991). In the former two studies, IS could be presented during a 10-s 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 participants were able to rehearse during the retention interval, simultaneous with the presentation of the IS. According to Jones and colleagues (Beaman & Jones, 1997, 1998; Macken et al., 1999), 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 presented again in rehearsal. Their commitment to this view is clear from statements made in a number of their articles. In discussing the locus of the IS effect, Beaman and Jones (1997) claimed 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) stated that "the prediction [that IS during the list and IS 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) proposed 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 acknowledged that there is no independent evidence that this is so in practice. Indeed, one obvious way to perform 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 (1996) offered an explanation of the IS effect in terms of temporal distinctiveness theory (TDT, Glenberg, 1987; Glenberg & Swanson, 1986). In his basic account, it was assumed 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 in either the 5 s before list presentation, the first 5 s of presentation, the last 5 s of presentation, the first 5 s of retention, or the last 5 s 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 stated,

> 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 went 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” (p. 420).

All three of these models (O-OER, feature theory, and 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-s retention interval. Although they did have a condition in which 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 come 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 that 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 articles by Jones and colleagues (Beaman & Jones, 1997, 1998; Macken et al., 1999) that we presented indicate, they still maintain that the IS effect is mediated by its effect on rehearsal. In their defense, 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 did 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 (1996) TDT, Nairne’s and Neath’s feature model (Nairne, 1990; Neath, 2000) and Jones’s (1993) O-OER theory all predict that any retroactive effect of IS depends on rehearsal. The other competing explanation of the IS effect is the one supplied by the WM model. However, this model is underspecified in that it makes no direct prediction about the point in time at which 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

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 was 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 that were in turn followed by an equals sign. The letter, digits, and equals sign were all presented singly at a rate of one every 750 ms. 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 absent altogether or could be present either during the letter-list presentation, during the digit/equals-sign presentation, or during both.

Method

Participants. The participants were 16 students from the University of Bristol, Bristol, United Kingdom, who were paid U.K.£4.00 (U.S.$6.00) for their participation. In this experiment, and in all of the experiments reported here, all participants were native speakers of English.

Materials. Sixteen participants were presented with lists of four 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 center 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 750 ms. Items were displayed for 650 ms, followed by a blank period of 100 ms. The word *Recall* appeared on the screen 100 ms after the equals sign disappeared. 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 in either of the two preceding lists, and no sequence of three letters 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 some trials, participants heard excerpts of Finnish speech, played at a comfortable volume, through headphones. (Colle, 1980, and Ellermeier & Hellbrück, 1998, have shown that the IS effect is largely independent of the loudness of the speech.) A female native Finnish speaker reading from a novel had recorded the Finnish speech onto a digital audiotape recorder. 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 3 or 6 s in length. Where necessary, pauses in the speech were edited out so that the speech sounded fluent and continuous to listeners who were not Finnish. 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 3 s of speech that started 50 ms before the visual presentation of the first letter and ended 50 ms before the onset of the first digit (IS during list); in a third condition, participants heard 3 s of speech that started 50 ms before the onset of the first digit and continued until 50 ms before the word *Recall* (IS during sum); and in the fourth condition, participants heard 6 s of speech that started 50 ms before the first letter and continued until 50 ms 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 4; each group saw 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 be marked only 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 accurately performing the task. 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

We show the mean percentages of items correct for the four IS conditions in Table 1. To be marked as correct, an item had to appear in the correct recall position; this criterion was applied to all of 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 by using a lax criterion according to which 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 was a large effect of IS on recall when the IS was presented throughout the trial, and this effect was approximately halved when the IS was presented simultaneous with either the letters or the digits. To confirm this interpretation, we ran a 4 (IS) $\times$ 4 (serial position) repeated measures analysis of variance (ANOVA). This analysis revealed statistically significant effects of IS condition, $F(3, 36) = 8.14$, $p < .01$, and serial position, $F(3, 36) = 14.40$, $p < .01$, with no significant interaction between the two, $F(9, 108) = 1.44$, $p = .18$. (Effects of serial position are found throughout this article and reflect entirely standard serial position curves; for this reason, and to avoid complicating the presentation of the results, we do not report the means for each serial position.) To test the more specific pattern of results across conditions, we conducted planned comparisons of 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 ps $< .05$), 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 ($p = .02$), and that there was a suggestion of a difference between the IS during list and IS throughout conditions ($p = .06$).

Table 1
Mean Values of Percentage of Items Correct, Collapsed Across Serial Position, for the Conditions of Experiment 1

Condition	% correct	
	M	*SE*
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

Note. IS = irrelevant sound.

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, had 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 Experiments 2–5, we build on this result by showing that a retroactive effect of IS persisted even when we used an overt speeded digit-reading task to prevent rehearsal.

Experiment 2

In Experiment 2, 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. In Experiments 2–5, therefore, we 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 involved 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 10-s retention interval. Although the standard procedure used to prevent rehearsal is AS, the rate and difficulty of the suppression task varies widely, and it is sometimes difficult to ensure that participants comply with instructions. Moreover, AS 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 with standard suppression, the digit-reading task enables the experimenter to control the rate of speaking, 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 750 ms. In pilot work, participants reported being unable to rehearse at this rate, and some found it impossible to keep up with faster rates of presentation. Note that Beaman and Jones (1997), in their study of IS, considered that AS 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 750 ms is a much harder task. In Experiment 5, we present data collected with a reading rate of one digit every 500 ms. 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.

Many researchers have suggested that the contribution of phonological STM to the serial-recall task is short-lived, perhaps being lost after as few as 3 s 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 30 s of backward counting, a retention interval presumably sufficient to abolish the use of the phonological store at retrieval. However, as we noted in the introduction of this article, other studies have emphasized the dependence of the IS effect on encoding within the phonological store (Hanley, 1997; Salamé & Baddeley, 1982).

We designed Experiment 2 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 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 3–6 s (Bjork & Healy, 1974). In Experiment 2, we included 6 confusable letters in the 12-letter stimulus set and tested recall after periods of 3, 9, and 12 s.

Method

Participants. The participants were 30 students from the University of Cambridge, Cambridge, United Kingdom, who were paid U.K.£3.50 (U.S.$5.50) for their participation.

Materials. Participants saw lists of 4 letters, presented in the same manner and with the same timing as they were in Experiment 1. On a given trial, the list comprised an ordering of either the set *BDPY* (3 phonologically confusable and 1 nonconfusable), the set *FSXQ* (3 phonologically confusable and 1 nonconfusable), or the set *HRJZ* (4 nonconfusable), with these three sets 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 researchers (Baddeley, 1968; Bjork & Healy, 1974; Henson, Norris, Page, & Baddeley, 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 1 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 maximize our chance of observing a PS effect by including 3 rhyming letters in each mixed list while, at the same time, balancing the occurrence of confusables and nonconfusables across conditions and serial positions. There were 24 possible orderings of each of the three letter sets. To give good experimental power, we let participants see 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. The word *loud* appeared on the screen 100 ms after the disappearance of the final letter (i.e., 750 ms after the final letter's onset), and participants were required to read it aloud. The word *loud* was selected to remind participants to switch from silent reading to reading aloud at this point in the trial. Like the letters, the word remained on the screen for 650 ms, followed by 100 ms of blank screen. There followed a number of individual digits that participants were required to read aloud. These appeared at a rate of 1 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 interonset interval. This rate of digit reading was taken to be sufficient to prevent subvocal rehearsal, and the experimenter monitored the quality of reading 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-subject 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 s, respectively. We chose these retention intervals because the phonological loop might be still in use at 3 s but would not be at 9 and 12 s. Moreover, we wished to compare performance at 9 and 12 s to see whether an asymptote in performance was being approached at these comparatively long retention intervals.

The presence of IS was also manipulated within subjects. On half of the trials, the first 3 s of the retention interval were accompanied by 3 s of IS presented over headphones in the same way as it was in Experiment 1. The IS stimuli were the same as those used in Experiment 1, and participants were asked to ignore the IS as best they could. On the other half of the trials, participants heard white noise during the first 3 s 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 & 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 six groups of 5, and each 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 PS and IS would diminish with increasing retention interval.

Results

The experimental data were subjected to a 2 (IS) × 2 (confusability) × 3 (delay) × 4 (serial position) repeated measures ANOVA. We give the values for the mean percentage of items correct, collapsed across serial position, in Table 2.

There were main effects of IS, $F(1, 24) = 13.60$, $p < .01$; delay, $F(2, 48) = 49.40$, $p < .01$; and serial position, $F(3, 72) = 62.20$, $p < .01$, but no main effect of confusability, $F(1, 24) = 2.60$, $p = .12$. None of the interactions between these factors approached statistical significance. In particular, the potentially interesting IS × Delay interaction was not reliable ($F < 1$). Performance declined rapidly, even over these fairly short filled retention intervals, appearing to reach something of an asymptote at the two longer intervals (9 and 12 s). Note that this asymptote was still well above chance levels of performance, which can be no more than 25% correct. A small but reliable effect of IS was present even at the longer delays, as was confirmed by planned contrasts at the 9- and 12-s delays, that gave $t(29) = 2.40$, $p = .01$, and $t(29) = 1.80$, $p = .04$, 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 it is not refreshed by an articulatory control process implementing rehearsal. The results of this experiment suggest that even after as few as 3 s 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 s, we have found strong effects of both PS and IS.

One should perhaps not be too surprised to find effects of IS outliving the effective contribution of phonological STM. As noted earlier, Colle and Welsh (1976) found a numerically similar (3%) effect of IS even after 30 s 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

Table 2
Mean Values of Percentage of Items Correct, Collapsed Across Serial Position, for the Conditions of Experiment 2

Retention interval and letters	IS condition: Speech *M*	Speech *SE*	Noise *M*	Noise *SE*	IS effect	Confusability effect
3						
Nonconfusable	67.2	2.9	70.3	2.2	2.0	0.4
Confusable	69.1	2.4	68.0	2.0		
9						
Nonconfusable	55.5	3.0	58.0	2.6	3.9	−3.7
Confusable	56.0	2.5	61.2	2.8		
12						
Nonconfusable	52.6	2.7	56.7	2.5	2.3	−3.7
Confusable	58.1	2.6	58.6	2.4		

Note. IS = irrelevant sound.

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 many as 12 s. There was no indication of a PS effect at all in this experiment, and the overall level of performance was 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 Experiment 3, 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 0.75 s along with delays of 3 and 12 s. 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 we used such simultaneous presentation.

Experiment 3

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 in Experiment 2, participants were asked to read aloud the word *loud* followed by digits appearing at a rate of one every 750 ms. The three retention intervals used 0, 3, and 15 digits giving retention intervals of 0.75 s, 3 s, and 12 s, respectively. Retention interval changed randomly from one list to the next; there was an equal number of each overall. Each list was accompanied by 3 s of either IS (Finnish) or white noise, again balanced within subject. IS was simultaneous with list presentation in this experiment owing to the requirements of the 0.75 s retention interval.

Method

Participants. Participants were 36 members of the MRC Cognition and Brain Sciences Unit, Cambridge, United Kingdom, participant panel, between the ages of 17 and 38 years, who were paid U.K.£3.50 (U.S.$5.50) for their participation.

Materials. The IS and white-noise materials were the same as those used in Experiments 1 and 2. A reviewer of a draft of this article expressed a concern that because *Y* can represent a vowel (although the letter name itself is not pronounced as a vowel), it might have facilitated recall of lists in which it was present. We therefore replaced the letter *Y* in the set *BDPY* with the letter *L*. We originally chose the letter *Y* to ensure 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 containing the letter 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 than did those in other groups.

Results

We show the means for the various conditions in Table 3. We analyzed results by using a 2 (IS) × 2 (confusability) × 3 (retention interval) × 4 (serial position) repeated measures ANOVA. Note that confusability refers here, and always, to items, not lists. The single nonconfusable items that appeared in lists with three

Table 3
Mean Values of Percentage of Items Correct, Collapsed Across Serial Position, for the Conditions of Experiment 3

Retention interval and letters	IS condition: Speech *M*	Speech *SE*	Noise *M*	Noise *SE*	IS effect	Confusability effect
0.75						
Nonconfusable	84.3	2.2	87.9	1.7	2.7	5.5
Confusable	80.0	2.3	81.8	2.2		
3						
Nonconfusable	68.3	3.1	73.7	2.9	5.0	1.7
Confusable	67.1	3.2	71.6	3.2		
12						
Nonconfusable	54.6	3.3	56.3	3.3	2.7	−1.7
Confusable	55.3	3.9	59.0	3.5		

Note. IS = irrelevant sound.

confusable items were treated as nonconfusable in this analysis. This revealed main effects of IS, $F(1, 30) = 16.50$, $p < .01$, with worse performance for IS than for noise; retention interval, $F(2, 60) = 98.70$, $p < .01$, with worse performance for longer retention intervals; and serial position, $F(3, 90) = 87.90$, $p < .01$, consistent with standard serial position curves. As in Experiment 2, the effect of IS was significant even at the 12-s delay, $t(35) = 2.00$, $p = .03$, one-tailed. There was no main effect of confusability, $F(1, 30) = 2.40$, $p = .13$. The theoretically interesting IS $\times$ Delay, $F(2, 60) = 1.20$, $p = .32$, and IS $\times$ Phonological Confusability interactions, $F(1, 30) < 1$, $p = .88$, did not approach statistical significance. The only significant interaction was Confusability $\times$ Delay, $F(2, 60) = 6.00$, $p < .01$, 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 0.75-s retention interval, $t(35) = 3.30$, $p < .01$. Once again, there was a small but unreliable advantage for phonologically confusable letters at the longest retention interval.

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 feasible only at the shortest retention interval. Nonetheless, the IS effect shows no such interaction with delay.

Discussion

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

There was an effect of confusability at short retention intervals that disappeared as the retention interval increased. 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 3 s cannot be attributed to a difference in the initial encoding process. It seems, therefore, that the effects of PS and 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 we discuss it further in relation to Experiment 4. 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

In Experiments 2 and 3, we showed 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 that runs counter to previous findings noted in the introduction to this article? Or is it perhaps sufficient for an effect of IS that the list has at some point entered the phonological store, regardless of whether that store is subsequently used at retrieval? In Experiment 4, 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 looking at the retroactive effect of IS when combined with AS during list presentation. AS 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 AS 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, Hanley (1997) and Salamé and Baddeley (1982) found that AS 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. In Experiment 4, therefore, we examine the effect of AS at input on the retroactive IS effect.

Method

Participants. The participants were 32 members of the MRC Cognition and Brain Sciences Unit participant panel, between the ages of 16 and 40 years, who were paid U.K.£3.50 (U.S.$5.50) for their participation in the experiment. None had taken part in Experiments 1, 2, or 3.

Materials, design, and procedure. The lists were identical to those seen in Experiment 2;[1] the total letter set comprised six confusable letters and six nonconfusable. The four-letter lists were presented at a rate of one item every 750 ms, comprising a 650-ms presentation of the letter, followed for 100 ms by a blank screen. The letters were followed, in the same rhythm, by the word *loud* followed by 11 digits selected as they were in Experiments 1–3. These 12 items therefore lasted 9 s. Participants were required to view the letters and then to read aloud the word *loud* and the subsequent digits. In half of the trials, participants were also required to perform AS during presentation of the letters. This consisted of repeatedly saying the word *racket* at a rate of approximately two times per second. Because the lists were presented visually, we expected that AS during input would prevent any verbal recoding of the letters, thus denying participants access to the phonological-loop component of STM.

To avoid complicating an already complex task, AS was blocked, with half of the participants suppressing for the first block of 72 trials and the remaining participants suppressing for the second 72 trials. In a random half of the trials, participants heard 6 s of irrelevant Finnish speech located centrally in the 9-s 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, participants were instructed to ignore the IS and white noise. There were two different mappings of lists to IS conditions, each of which was seen by half of the participants. Crossing these mappings with the blocking of AS produced four groups of participants. 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

[1] We ran Experiment 4 before Experiment 3. It is for this reason that the letter *Y* is still used as one of the nonconfusables in Experiment 4.

trials were constructed from the letters *GKLN,* and there were equal numbers of each IS condition.

Results

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

We show the means for the various conditions, collapsed across serial position, in Table 4. There were main effects of IS, $F(1, 28) = 4.40$, $p < .05$; suppression, $F(1, 28) = 19.10$, $p < .01$; confusability, $F(1, 28) = 4.53$, $p < .04$; and serial position, $F(3, 84) = 27.50$, $p < .01$. 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 were nonconfusable letters in 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. It is in accord 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 participants guess the items but provides no information about item position.

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, $t(31) = 2.71$, $p = .01$, that disappeared with suppression, $t(31) = 0.14$, $p = .90$. In fact, under suppression, the error rates for the IS and no-IS conditions were 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, $t(31) = 1.86$, $p = .04$. Note that in a standard ANOVA, the Suppression $\times$ IS interaction gave $F(1, 28) = 3.43$, $p = .08$. With this *F* test, we tested the two-tailed hypothesis, asking whether the effect under suppression was smaller or bigger than that found with no suppression. Treating this as a directional test of the specific prediction made here gave $p = .04$, which was entirely equivalent to the arguably more familiar one-tailed *t* test.

Discussion

Hanley (1997) and Salamé and Baddeley (1982) both found that there was no IS effect for visually presented lists with AS 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 of these findings, Experiment 4 shows that this retroactive IS effect also disappears when participants must suppress during presentation. The results of Experiment 4 therefore confirm that the effect of IS is specific to the retention of order in the phonological store, and, furthermore, suggest that it is encoding in the phonological store that leads to an IS effect, not necessarily retrieval from it. These data therefore allow us to 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) 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” 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 STM. Whether IS disrupts short-term recall depends critically on whether information is, or has been, held in the phonological store.

Experiment 5

One concern that might be raised regarding Experiments 1–4 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

Table 4
Mean Values of Percentage of Items Correct, Collapsed Across Serial Position, for the Conditions of Experiment 4

Condition and letters	IS condition: Speech *M*	Speech *SE*	Noise *M*	Noise *SE*	IS effect	Confusability effect
No suppression						
Nonconfusable	60.4	3.3	64.6	3.2	3.6	−0.5
Confusable	61.5	3.1	64.5	2.9		
Suppression						
Nonconfusable	51.8	3.4	52.6	3.5	0.2	−4.4
Confusable	56.8	3.6	56.3	3.4		

Note. IS = irrelevant sound.

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 0.75 s to approximately 55% correct after 9 or 12 s. We know very well that if participants are allowed to rehearse, they can maintain recall of a four-item list virtually indefinitely. Even a seven-item list can be recalled at 80% correct after an unfilled 10-s delay (Jones & Macken, 1995, Experiment 4). If participants were able to rehearse under our conditions, then how can we explain their asymptotically poor performance after 9 s? 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 having used phonological STM at retrieval. Consistent with previous research, the PS effect was removed by delays of as few as 3 s. This is in contrast with Jones and Macken's finding (in their Experiment 4) that the PS effect survives a 10-s unfilled retention interval in which rehearsal is not prevented even for a seven-item list. The PS effect even reversed in our Experiment 4, consistent with Nairne and Kelley's (1999) findings.

On the basis of these considerations, we are confident that, in Experiments 2–4, speeded digit reading indeed prevented subvocal rehearsal during the retention interval. Clearly, however, it is impossible to prove absolutely that participants were never rehearsing. In Experiment 5, 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 U.K.£5.00 (U.S.$8.00) for their participation.

Materials, design, and procedure. In Experiment 5, we used the same four-item lists that we used in Experiment 3. After each list, participants were presented with the word *loud* followed by 11 digits at a rate of 1 every 500 ms. Participants were asked to read both the word *loud* and the digits, as in Experiments 2–4. During the resulting 6-s retention interval, participants heard either 6 s of Finnish speech or 6 s of noise. The reading rate used in this experiment is about the fastest our participants could manage reliably and is the same rate as was used, for the same purpose, by Nairne and Kelley (1999). At the end of the experiment, all participants were asked whether they had been able to rehearse any of the letters while reading the digits. Note that before this, participants were not informed that the purpose of the digit-reading task was to prevent their rehearsing.

Table 5
Mean Values of Percentage of Items Correct, Collapsed Across Serial Position, for the Conditions of Experiment 5

	IS condition				
	Speech		Noise		
Letters	*M*	*SE*	*M*	*SE*	IS effect
Nonconfusable	60.4	3.5	64.4	3.5	4.0
Confusable	59.2	3.8	60.6	3.7	1.4
Confusability effect	1.2		3.8		

Note. IS = irrelevant sound.

Results

We show the results of Experiment 5 in Table 5. None of the participants reported being able to rehearse any of the letters while reading the digits. The data were analyzed using a 2 (IS) $\times$ 2 (confusability) $\times$ 4 (serial position) repeated measures ANOVA. There were significant main effects of IS, $F(1, 23) = 7.50$, $p = .01$, with performance worse with speech than with noise, and serial position, $F(3, 69) = 35.60$, $p < .01$. The main effect of PS was significant, $F(1, 23) = 4.30$, $p = .05$.

Discussion

Experiment 5 provides further confirmation of a retroactive IS effect under conditions in which we can be as confident as it is possible to be that participants were unable to rehearse. Regardless of what the mechanism of the retroactive IS effect is, it is not mediated by its influence on rehearsal. Finally, we note that although 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 effect (Experiment 2) and the standard simultaneous effect of IS (Experiment 3) persist at delays of up to 12 s. 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 (Beaman & Jones, 1998; Macken & Jones, 1995; Macken et al., 1999; Miles et al., 1991) 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 of performing 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 500 ms. 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 (1996) TDT, Nairne's and Neath's feature model (Nairne, 1990; Neath, 2000), and Jones's (1993) O-OER model. In all of these accounts, the IS must be presented simultaneously with the to-be-remembered items or their rehearsal in order to have its effect (see the various quotes to this effect in the introduction to this article). 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 AS during visual presentation. Experiment 4 confirms earlier results on the effect of suppression on simultaneously presented IS (Hanley, 1997; Salamé & Baddeley, 1982). 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, in which it is assumed that the representation of serial order in STM is amodal. Even when suppression prevents visual material from being phonologically recoded, participants 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 s (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 the longer-term store.

As we noted in the introduction to this article, data from Hanley (1997) and Salamé and Baddeley (1982) suggest that there is no IS effect with AS at input for visual lists. The standard WM explanation of these results is that suppression prevents information being recoded into the phonological store and that participants must rely on one or more alternative stores. Baddeley (2000a) 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, which 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 observed 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 & Shaibe, 1997) and that sounds other than speech also interfere with memory (Jones & Macken, 1993; Klatte et al., 1995; Salamé & Baddeley, 1989) allow us to 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 to this article, an attentional explanation must recognize that the IS effect is dependent on the involvement of the phonological store.

Page and Norris (2003) 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 STM. 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 (2003) have presented simulations of IS data from Larsen and Baddeley (2003) using the primacy model. According to Page and Norris, IS has its effect on specific order-representing resources in phonological STM and, hence, on the representation of the to-be-remembered list. Like 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 of representing 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 (2003), one can accurately fit the data by simply 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 that represents order in the to-be-remembered list and another gradient that represents order in the IS. This assumption is consistent with the changing-state hypothesis. To the extent that the IS does not change state, it should not place demands on a mechanism specifically designed for storing order in STM.

Page and Norris (2003) 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 that represents a list of confusable letters looks no different from the one that represents 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. According to 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 IS 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 that represents the to-be-remembered list and 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 at which the loop no longer contributes to recall (as is demonstrated 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 in which 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 long-term memory (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 the 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 represented more weakly, 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 modeled (Page & Norris, 1998) in terms of confusions in the recall process from the phonological store, but it is important to note that it does not depend on a weakening of the primacy gradient itself. PS should not, therefore, 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, in the present experiments, we 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 (1996) TDT, Jones's (1993) O-OER and Nairne's and Neath's feature model (Nairne, 1990; Neath, 2000). We have also shown that AS 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 AS eliminates the effect of IS during input of visual lists is because suppression prevents the phonological recoding of visual material. The effects of both simultaneous and retroactive IS appear to be on the phonological store and, we hypothesize, on whatever system for longer term ordered memory the store affects.

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