

The Role of Intentional Forgetting in Reducing Children's Retroactive Interference

Mark L. Howe
Lakehead University

Preschool and kindergarten children's retention of stories was examined in the presence of interfering information and instructions to forget. Children learned 2 stories and, 24 hr later, were asked to recall the 1st or 2nd story learned. Some of the children were instructed, either following acquisition or just prior to the retention test, to forget the 2nd, or interfering, story. A model was used to isolate storage and retrieval effects, and the results showed that (a) retroactive interference affected both storage- and retrieval-based forgetting rates for the younger children but only storage-based forgetting rates for the older children, (b) intentional forgetting reduced retroactive interference primarily by attenuating storage-based forgetting regardless of age, (c) intentional forgetting instructions were effective only at acquisition for preschoolers but at both acquisition and retention for kindergarteners, and (d) all children recalled the to-be-forgotten story as well as they recalled the to-be-remembered story. These results are interpreted in terms of reorganization and distinctiveness effects in storage.

For some time now, there has been active debate concerning how best to reduce the effects of misinformation on recall of eyewitnessed events. Nowhere has this controversy flourished more vigorously than in the study of eyewitness memory of young children, who are said to be more susceptible to memory distortion effects than are older children and adults (for a review, see Ceci & Bruck, 1995). In these studies, memories for witnessed events are examined following the presentation of other, oftentimes contradictory information that serves to interfere with memory for the original event. This information is usually presented in the form of additional events, narratives, or suggestive and leading questions. The key result is that memories for the original information and the misleading information become confused, with recollection of the original event becoming tainted or interfered with by the subsequent information. These confusions occur not only in laboratory settings but also in remembrances of real-life events, including memories for medical examinations (e.g., Bruck, Ceci, Francoeur, & Barr, 1995), anticipated medical procedures such as the voiding cystourethrogram (e.g., Goodman, Quas, Batterman-Faunce, Riddlesberger, & Kuhn, 1997), as well as unexpected traumatic occurrences involving physical injury (e.g., Howe, Courage, & Peterson, 1995). Despite its significance, the question of whether these interference effects are the result of changes to (or interference among) traces already in memory storage or are the result of response competition between two or more traces at the time information is being retrieved has not been resolved. In any event,

it is both forensically and theoretically important to determine the best way to reduce interference between memory for original event information and memory for subsequently encountered information.

The literature on intentional forgetting may provide a potential solution to this intransigent problem. Recently, the extent to which individuals can control or direct the contents of their memories has emerged as an important issue in the forgetting literature. For example, in forensic settings there have been frequent claims by adults that they have forgotten, intentionally or otherwise, memories of childhood trauma. Moreover, it has been observed empirically that forgetting can be advantageous to memory, particularly if the to-be-forgotten information is outdated or interferes with more adaptive behavior (e.g., Kraemer & Golding, 1997; Riccio, Rabinowitz, & Axelrod, 1994). It may be possible, then, to reduce interference effects arising from the acquisition of new and potentially misleading information by attempting to have subjects forget the interfering (mis)information. Before describing such an experiment with young children, I provide a brief overview of the retroactive interference and intentional forgetting literatures.

Retroactive Interference

The study of retroactive interference effects, like the study of intentional forgetting, has enjoyed a long history in the adult literature on memory and retention (for reviews, see Crowder, 1976, and Postman & Underwood, 1973). The origins of the storage versus retrieval debate can be found in this literature. The retrieval side was represented by investigators such as McGeoch (1942), who viewed interference as arising from response competition. That is, at retrieval, responses from both the early and later learned materials were thought to compete for output, with the ordering in the output queue being determined by such things as recency (i.e., last in, first out). Alternatively, storage theorists (e.g., Melton & Irwin, 1940) argued that interference occurred because the earlier memory trace was altered by the acquisition of the subsequent information (e.g., associations became unlearned).

Preparation of this article and the research reported herein were funded by Grant OGP0003334 to Mark L. Howe from the Natural Sciences and Engineering Research Council of Canada.

I thank Chuck Brainerd and Mary Courage for helpful comments on an earlier version of this article.

Correspondence should be addressed to Mark L. Howe, Centre of Excellence for Children and Adolescents With Special Needs, 954 Oliver Road, Lakehead University, Thunder Bay, Ontario P7B 5E1, Canada. E-mail: mark.howe@lakeheadu.ca

These two proposals were tested in a classic experiment by Barnes and Underwood (1959) in which they used the *modified modified free recall* (MMFR) procedure. They reasoned that if interference was due simply to the competition between two responses at output, then allowing subjects as much time as they needed to recall both responses should eliminate interference. Alternatively, if interference was due to unlearning modifications in storage, then the MMFR procedure should not reduce the amount of interference. Although initial findings appeared to support the storage interpretation of retroactive interference, a number of later results contradicted or were inconsistent with the unlearning hypothesis, leading Barnes and Underwood to construct a compromise hypothesis in which both storage and retrieval components played a role in retroactive interference (see Bower, Thompson-Schill, & Tulving, 1994). However, the issue remains unresolved because certain theorists retain the idea that interference is retrieval based (e.g., Gillund & Shiffrin, 1984; Mensink & Raaijmakers, 1988), whereas others argue that it arises from processes operating at storage (e.g., Ackley, Hinton, & Sejnowski, 1985; Metcalfe, 1990; Murdock, 1982).

In research with children, although there have been numerous investigations of misinformation effects that have used the eyewitness memory paradigm, there have been only two reports in which retroactive interference was examined directly. In one of these, a series of experiments by Koppenaal, Krull, and Katz (1964), 4-, 5-, and 8-year-olds learned two lists of paired associates using the same stimuli but different responses. Following a 24-hr retention interval, children in the retroactive interference and MMFR groups recalled fewer List 1 responses than did children in a control condition in which only a single list was learned. Counterintuitively (e.g., see Ceci & Bruck, 1995), the magnitude of interference effects in the Koppenaal et al. (1964) study increased with age such that 8-year-olds exhibited more interference than did 4- and 5-year-olds. Indeed, these younger preschoolers exhibited almost no interference at all.

More recently, in a study that used formal modeling techniques to provide estimates of storage and retrieval contributions to children's long-term retention, preschool and kindergarten children's retroactive interference was examined with both free and cued recall (Howe, 1995). Using longer lists than Koppenaal et al. (1964) and both one-trial and criterion acquisition procedures, that study found large interference effects, although there were no age differences in these effects. It is interesting that the locus of retroactive interference was primarily at storage. That is, learning a second list affected what had been stored about the first list and not simply the retrieval of that earlier learned information.

What these studies make clear is that young children are susceptible to interference effects, although at least according to the Koppenaal et al. (1964) study, perhaps they are less susceptible than older children. Moreover, it seems that the MMFR procedure does not provide much release from retroactive interference, a finding that has been obtained a number of times with adults (e.g., Bower & Mann, 1992). Finally, consistent with some recent theories of memory, the locus of interference effects is primarily at storage, at least over a 24-hr retention interval.

Intentional Forgetting

Although the exact mechanism by which intentional forgetting operates is not clear, recent evidence from studies with adults

indicates that most of the findings can be accommodated by a model that involves processes of segregation, selective rehearsal, selective search, and inhibition (e.g., MacLeod, 1998). Here, to-be-remembered information and to-be-forgotten information are segregated in memory, with selective rehearsal occurring when cuing (remember, forget) occurs early in the encoding process or prior to long-term retention. During retrieval, a selective search for the to-be-remembered information takes place, and inhibition of to-be-forgotten items at output can occur if they are mistakenly selected by the search process. Thus, in most models, both storage and retrieval factors contribute to memory performance.

To date, research on intentional forgetting in children has been restricted to school-aged children, because it has generally been assumed that younger children lack or are unable to execute certain of the prerequisite skills, most notably the inhibitory mechanisms necessary to suppress information and the strategic skills needed to mediate differential rehearsal. Among school-aged children, age differences in intentional forgetting are thought to be controlled by changes in the very same mechanisms and processes that have been proposed to control intentional forgetting in adults (for a review, see S. P. Wilson & Kipp, 1998), which provides yet another example of the continuity of cognitive processes across development. For example, using item-based intentional forgetting instructions in which children are told to forget specific list members, a number of researchers have found that older children, compared with younger children, will selectively rehearse the to-be-remembered items, thereby producing better recall of these items than of the to-be-forgotten ones (e.g., Foster & Gavelek, 1983; Lehman & Bovasso, 1993; Posnansky, 1976). Selective rehearsal of to-be-remembered items has also been found to be important in conditions where entire lists are cued (e.g., Bray, Justice, & Zahm, 1983; Posnansky, 1976). Accordingly, age-related increases in children's ability to intentionally forget information under these conditions are often linked to changes in their ability to execute selective rehearsal strategies. Other investigators, using either item-based, blocking (forget specific subsets of items), or list-based (forget an entire list) intentional forgetting instructions, have found evidence of retrieval inhibition (e.g., Harnishfeger & Pope, 1996; Lehman & Bovasso, 1993; Lehman, McKinley-Pace, Wilson, Slavsky, & Woodson, 1997). That is, instead of finding poorer storage that may result from less rehearsal, these investigators found that items were equally well encoded and stored but were then inhibited at the point of retrieval. Here, age-related increases in the ability to intentionally forget information are linked to more general developments in children's cognitive inhibition (e.g., see S. P. Wilson & Kipp, 1998). Finally, Lehman, Morath, Franklin, and Elbaz (1998) found another source of children's errors in intentional forgetting tasks, namely, their poorer ability to encode or segregate the *remember* or *forget* cues. In a series of experiments with children in Grades 2, 4, and 6 and college students, they found that children were not as good as adults at encoding information about whether an item should be forgotten or remembered. That is, children were less able than adults to segregate a given memory item into *to-be-remembered* or *to-be-forgotten* categories.

Overall, then, age differences in the ability to intentionally forget information could be due to developmental changes in storage (e.g., poorer rehearsal of information leading to degraded traces), in keeping information distinctive once in storage (e.g., remembering which items or lists belong in the *forget* pile and the

remember pile), or in retrieving information (e.g., inhibiting to-be-forgotten items at output). Like other areas of memory research, then, there is controversy concerning whether storage factors, retrieval factors, or both control intentional forgetting.

The Present Research

Conceptual Issues

The research reported here was designed to address four interrelated objectives. The first was to establish the presence and locus of retroactive interference effects in preschool and kindergarten children's long-term retention by using material (stories) more integrated than that used in previous research (Howe, 1995; Koppenaal et al., 1964). The expectation was that such internally cohesive materials would be less subject to interference effects than would a list of unrelated concepts. Alternatively, because the stories learned were very similar, even greater interference might be observed.

The second objective was to demonstrate intentional forgetting effects in preschoolers. These children have typically been excluded from intentional forgetting research on the assumption that they lack important prerequisite skills, most notably the ability to inhibit verbal information. This presumed deficiency rests on evidence that the prefrontal cortex, so critical in the development and deployment of inhibition, is markedly immature in preschoolers. However, other research (though not examining intentional forgetting per se) has shown that young children can indeed inhibit verbal information in some conditions. For example, Lewis, Stanger, and Sullivan (1989) found that 3-year-olds suppressed information about having peeked at a forbidden toy in spite of video evidence to the contrary. Similarly, Bottoms, Goodman, Schwartz-Kenney, Sachsenmaier, and Thomas (1990) reported that 5-year-olds omitted information about an incident their mothers had asked them to keep secret (see also J. C. Wilson & Pipe, 1989). Indeed, Pipe and Wilson (1994) showed that 6-year-olds were more likely than 10-year-olds to keep information secret even after a 10-week retention interval. Although these latter studies did not establish that the material to be kept secret was actually still in memory at test, its distinctiveness (e.g., accidentally spilling ink) made its retention highly likely (see Howe, Courage, Vernescu, & Hunt, 2000).¹

If retroactive interference and intentional forgetting effects were found, the third objective was to determine whether intentional forgetting instructions could serve to reduce interference. If they could, the next question was whether the locus of the effect was at storage, retrieval, or both. A related issue was whether the timing of the intentional forgetting instruction mattered (i.e., right after acquisition or just prior to the retention test 24 hr later).²

The fourth objective was to determine the fate of the to-be-forgotten material. Here there were two important theoretical questions. The first was whether the information was actually forgotten (i.e., unavailable or inaccessible), whether it was not forgotten but inhibited at output, or whether it was enhanced in memory (e.g., through release from proactive interference; distinctiveness effects). The second was whether observed changes in performance were storage based, retrieval based, or both. To this end, half of the children who were instructed to forget the interfering story following acquisition were required to recall it at retention.

Analytical Issues

In order to determine whether storage or retrieval explanations (or both in combination) are the most appropriate for addressing these experimental questions, a method for divining theoretical processes from empirical performance is required. Because storage and retrieval are highly interrelated, latent, theoretical processes that cannot be directly observed in memory data, some formal method must be adopted in which the rules that map these theoretical forces onto performance outcomes are made explicit (see Batchelder & Riefer, 1999). One model that has been used successfully in studying the development of children's long-term retention processes, particularly the contributions of storage and retrieval to both forgetting and reminiscence processes, is the trace-integrity model. Because a lengthy review of this model and its mathematical and statistical properties has appeared in the literature (see Howe & O'Sullivan, 1997), only an overview of its critical features is presented here (see also the Appendix to this article).

¹ Some might argue that, in fact, different mechanisms underlie intentional forgetting and keeping a secret. For example, children might keep a secret out of fear of retribution or to comply with the experimenter; their secret keeping may have little to do with deploying inhibitory mechanisms. Indeed, it is well known that the veracity of forensic interviews with young children can be compromised by children's feelings of guilt, embarrassment, or fear in reporting traumatic or abusive events (e.g., Sgroi, Blick, & Porter, 1982; Summit, 1983). Although children may not report "forbidden" information that is present in memory, they still must inhibit its production during recall.

² In traditional designs, the administration of the intentional forgetting instruction at the time of acquisition would be associated with storage factors (e.g., reducing the probability of rehearsing the story during the retention interval), whereas when such instructions are given just prior to the test of retention, changes in performance due to intentional forgetting would be assigned to retrieval processes (e.g., inhibiting the recall of the second story at output). Unfortunately, these approaches to separating storage and retrieval processes often founder. This is because simply associating the timing of a manipulation (e.g., at acquisition vs. at retention) with the theoretical locus (e.g., storage vs. retrieval) of its effect is fraught with a number of serious problems. Because storage and retrieval are theoretical processes that are not directly observable in memory performance, such processes do not become any more directly observable in performance outcomes simply through the use of experimental manipulations. Even from a purely logical perspective, it should be obvious that both storage and retrieval processes can be involved in selective rehearsal following acquisition as well as when intentional forgetting manipulations are delivered just prior to retention testing. That is, selective rehearsal at acquisition can alter not only what gets into storage but also what retrieval routes are created and practiced in order to gain access to that stored information. Similarly, intentional forgetting manipulations that are administered just prior to retention might lead not only to suppression of retrieved information that is not to be recollected but also to the reorganization of that to-be-forgotten information in storage so as to make it more discriminable from the to-be-remembered information. In order to understand the relative impact of the timing of a manipulation such as intentional forgetting on the latent storage and retrieval components of memory, then, one cannot rely on simple empirical outcomes; rather, one must use a formal model to partition the outcomes in terms of the theoretical processes of interest. Thus, according to this logic, it remains an empirical question whether storage processes, retrieval processes, or both are affected by varying the timing of the intentional forgetting manipulation.

The basic assumption of this model, like so many other recent memory models (e.g., Estes, 1997; Tulving, 1984), is that storage and retrieval processes lie on a single continuum, with the integrity of the trace varying with the extent to which trace elements (features, nodes, etc.) are bound together into a whole. As memory traces are acquired, their elements are encoded and stored in some stable structure. Following this acquisition sequence, traces can either remain the same, lose their retrievability, or exhibit disintegration of their structural properties in storage over a retention interval. On subsequent tests of long-term retention, traces that do not lose their integrity exhibit correct response rates of 1 (no storage or retrieval failure). Those that experience some loss of integrity (making them difficult to access or retrieve) exhibit correct response probabilities that are less than 1 but greater than 0 (retrieval failure only). Finally, those traces with compromised structural integrity exhibit correct response probabilities of 0 (both storage and retrieval failure).

In addition to these forgetting processes, there exist trace reminiscence probabilities involving both storage and retrieval processes. That is, even though a retention session may consist of test trials only, with no additional, explicit learning opportunities (i.e., representation of list items), the possibility exists that traces can be reminisced through reinstating retrieval processes, for those items that underwent retrieval-based forgetting, or reintegrated in storage (e.g., Horowitz & Prytulak, 1969), for those items that underwent both storage- and retrieval-based forgetting.

These basic ideas have been implemented in a mathematical model that pertains to experiments that employ four test opportunities with no further study. A description of the various parameters that measure storage failures (S), retrieval failures (R), storage reminiscence (a), and retrieval reminiscence (the r_i and the f_i) is given in Table 1. In what follows, this trace-integrity model (along with more traditional analyses) is used to examine the role of storage and retrieval processes in young children's 24-hr retention of stories in the presence of interfering information and intentional forgetting instructions.

Table 1
Definitions of the Parameters in the Trace-Integrity Framework

Process and parameter	Description
Trace forgetting	
S	The probability of storage failure
R	The probability of retrieval failure of information in storage
Trace reminiscence	
a	The probability that information not in storage is reintegrated to a level above zero recall
r_1	The probability of two consecutive successes
r_2	The probability of three consecutive successes
r_3	The probability of four consecutive successes
f_1	The probability of a success following one error
f_2	The probability of a success following two consecutive errors
f_3	The probability of a success following three consecutive errors

Method

Subjects

The subjects were 120 (52 boys and 68 girls) 4-year-olds (mean age = 4 years 4 months; range = 3 years 11 months to 5 years 3 months) and 120 (57 boys and 63 girls) 6-year-olds (mean age = 6 years 1 month; range = 5 years 6 months to 6 years 4 months). The majority of the children were middle class, White, and from a predominantly metropolitan area. All participated with written parental consent.

Materials

Children learned either one or two stories concerning children going to a store. In one story, a boy or a girl (same sex as the subject) went to the toy store to buy a present for a friend. He or she examined a number of toys, games, and books and in the end decided to buy a ball. In the second story, a boy or a girl (same sex as the subject and with a different name than the child in the first story) went to the pet store to buy himself or herself a new pet, examined a number of different animals (e.g., fish, snakes), and in the end bought a puppy. Both stories were illustrated with color pictures and narrated by the experimenter.

Procedure

Preschool and kindergarten children were randomly assigned to one of the six conditions with the stipulation that the same ratio of boys to girls had to exist in each condition. As illustrated in Table 2, there were five experimental retroactive interference (RI) groups in which children learned both Story 1 and Story 2 (in counterbalanced order) at acquisition and were asked to recall one of the stories at a retention test 24 hr later. Two of these groups experienced standard retroactive interference and are designated $RI_{\text{Story 1}}$ and $RI_{\text{Story 2}}$ (the subscripted story number indicates which of the two stories they were to recall at retention testing). Three of these groups were also given intentional forgetting (IF) instructions—for two groups it occurred immediately after acquisition, and for one group it was just before the long-term retention test. These groups are designated $RI/IF\text{-acq}_{\text{Story 1}}$, $RI/IF\text{-acq}_{\text{Story 2}}$, and $RI/IF\text{-ltr}$, respectively. Table 2 also shows a sixth group, a control group in which subjects learned one of the two stories (half learned the story about the pet store and half the story about the toy store) and then returned 24 hr later and were tested four consecutive times on that story.

All stories were learned to a criterion of two consecutive errorless test trials. Children were tested individually in a small room in their school. The stories were read aloud by the experimenter and illustrated with colored pictures. Following the reading of the story, children engaged in some distractor activity (a matching symbols task) for 30 s, which was provided in order to prevent short-term memory effects. Following this distractor activity, children were presented with a series of 11, canonically ordered questions (cues) about the story they had just heard and were required to give a one-word response (e.g., "Who went to the store with his father?" Answer: "Jack"). Note that the questions were identical across the two stories—only the answers differed. That is, the design is identical to the more traditional AB-AC paired-associate study of retroactive interference effects in which the stimuli or cues (A) are the same for both lists but the responses or answers (B or C) differ across lists. This study-distractor-test procedure continued until the child was able to answer all 11 questions correctly on two consecutive test trials.

The stories were presented sequentially; that is, children learned the first story to criterion using the study-distractor-test procedure, and then they learned the second story. The average delay between the end of the final criterion test trial on the first story and the first study trial for the second story was 3 min (time enough for the experimenter to switch storybooks and instruct the child to try to remember the next story). Following acquisition of the second story, children in the intentional forgetting at

Table 2
Outline of Procedure Used to Study Children's Intentional Forgetting

Condition	Manipulations		
	Acquisition	Forgetting instructions	Story tested at retention
Control	Learn one story only		Story learned at acquisition
RI _{Story 1}	Learn Story 1, then Story 2		Story 1
RI _{Story 2}	Learn Story 1, then Story 2		Story 2
RI/IF-acq _{Story 1}	Learn Story 1, then Story 2	Instructed to forget Story 2 at end of acquisition	Story 1
RI/IF-acq _{Story 2}	Learn Story 1, then Story 2	Instructed to forget Story 2 at end of acquisition	Story 2
RI/IF-ltr	Learn Story 1, then Story 2	Instructed to forget Story 2 24 hours later, just prior to the retention test	Story 1

Note. RI = retroactive interference; IF = intentional forgetting; acq = acquisition; ltr = long-term retention.

acquisition conditions (the RI/IF-acq_{Story 1} and RI/IF-acq_{Story 2} groups) were told to forget the story they had just learned. That is, the experimenter acted flustered and told the child that she had made a mistake and should not have read the second story to him or her. She then instructed the child to simply forget the second story. Children in the intentional forgetting at long-term retention condition (RI/IF-ltr) received the same instructions just prior to the test of long-term retention 24 hours later.³

Twenty-four hours following acquisition, children were administered four test trials without additional study opportunities on the first or second story they had learned. The experimenter cued the subject as to which story to recall not only by asking for recall of the "first" (or "second") story but also by labeling the story ("Pet Store" or "Toy Store") and by referring to the color of the cover (green or blue) of the binder in which the story had appeared. Children again answered the 11 questions about the story and participated in a 30-s distractor task (symbol matching) before answering the 11 questions again. This test-distractor procedure continued until all four test trials were complete.

Results

Although the main focus of this section is on the trace-integrity model's detailed accounting of the effects of the retroactive interference and intentional forgetting on the storage and retrieval components of the development of children's long-term retention, the results of more traditional analyses of the global trends present in these data are reported first. An analysis of covariance (ANCOVA) was selected because it is one means by which to control possible under- and overlearning effects at long-term retention that are due to individual differences that carry over from initial acquisition (also see Howe, 1995). Through the use of performance differences during acquisition (e.g., total errors) as a covariate, any confounds that remain following (or might be caused by) criterion acquisition can be eliminated from the dependent variable (total errors per trial at long-term retention) prior to assessment of the impact of the manipulations of interest. Of course, specific mathematical models are needed as well because ANCOVAs do not represent a panacea for these problems, particularly inasmuch as they do not contain specific goodness-of-fit mechanisms, are general purpose and hence not theoretically motivated, and fail to isolate latent cognitive processes such as storage and retrieval (see Howe, 1995). For these and other reasons, mathematical models are more sensitive and considerably more powerful when used to examine specific hypotheses concerning the nature of children's long-term retention. Before these analyses

are presented, however, the global trends as detected by the ANCOVA are detailed.

Global Trends

First, the number of trials needed to reach criterion at acquisition (e.g., the trial of last error) did not differ with age ($M = 1.73$ for preschoolers; $M = 1.67$ for kindergarteners). Concerning long-term retention, total errors for each of the four trials at retention were analyzed with a 2(age: preschool or kindergarten) \times 6 (condition: control, RI_{Story 1}, RI_{Story 2}, RI/IF-acq_{Story 1}, RI-acq_{Story 2}, or RI/IF-ltr) \times 4 (trials: 1-4) ANCOVA in which total errors at acquisition served as the covariate (this tends to be a more sensitive index of acquisition differences than is trial of last error and hence was used for the purposes of the ANCOVA). The results indicated that there was (a) a main effect for the covariate, $F(1, 227) = 13.58, p < .01, \eta^2 = .072$; (b) a main effect for age, $F(1, 227) = 8.40, p < .01, \eta^2 = .046$, in which preschoolers made more errors ($M = 2.54$) than kindergarteners ($M = 1.38$); and (c) a main effect for condition, $F(5, 227) = 4.38, p < .01, \eta^2 = .111$. It is of note that these effect sizes of η^2 indicate that the proportions of variance of the dependent variable related to the factors in each condition are in the range from moderate to large. Post hoc Newman-Keuls tests ($p < .01$) of the main effect for condition indicated the following order of difficulty: [control ($M = 0.81$) = RI/IF-acq_{Story 1} ($M = 1.17$)] < [RI_{Story 2} ($M = 1.68$) = RI/IF-acq_{Story 2} ($M = 2.27$) = RI/IF-ltr ($M = 2.33$)] < RI_{Story 1} ($M = 3.22$). What these findings indicate is that there was marked retroactive interference. That is, as expected, children in the RI_{Story 1} condition committed more mean errors than did children in the control condition. Also as anticipated, this interference was reduced back to the level of that of control subjects given intentional forgetting instructions, but only when those instructions were given at acquisition (RI/IF-acq_{Story 1}). Children who were given the intentional forgetting instructions at the time of retention testing (RI/IF-ltr) exhibited very little release from retroactive

³ Note that which story (Story 1 or Story 2) was to be recalled 24 hr later was not manipulated for those receiving the intentional forgetting instruction just prior to the test of retention because asking children to recall something they had just been asked to forget was more confusing than probative.

interference, performing approximately as well as those who recalled Story 2 in the RI and RI/IF-acq conditions.

Finally, both the age and condition main effects were qualified by a first-order Age \times Condition interaction, $F(5, 227) = 2.72$, $p < .02$, $\eta^2 = .072$. As can be seen in Figure 1, the source of this interaction was an age difference in performance in the RI/IF-ltr condition. Here, although preschool children did not benefit from the intentional forgetting instruction, kindergarten children did. In fact, for the kindergarten children, this instruction reduced retroactive interference to the level of that in the control group in a manner similar to when it was given following acquisition.

The finding of retroactive interference in young children's long-term retention, even for story materials, is not unexpected and is consistent with previous reports involving more traditional list-learning procedures (Howe, 1995). It may be somewhat unusual that children so young should be able to benefit from intentional forgetting instructions, particularly if the effectiveness of intentional forgetting is mediated by later-developing changes in cognitive inhibition. That is, because cognitive inhibition is said to be rather immature during this age period, particularly in the preschool years (e.g., S. P. Wilson & Kipp, 1998), the children in this study may not have been able to benefit from such an instruction. Fortunately, however, the results clearly indicate that even preschoolers can benefit from such instructions although only when given right after acquisition of the to-be-forgotten list. That there was no reduction in retroactive interference when this instruction was given just prior to the 24-hr retention test is somewhat curious but does provide for a theoretically interesting limiting condition on these effects, at least with preschool-age children. The important thing shown by the Age \times Condition interaction was that kindergarten children could use intentional forgetting to reduce retroactive interference and restore performance back to the level

of that of control subjects. Although it might be tempting to conclude that these effects are storage based because retroactive interference was reduced when instructions to forget the second story were administered at acquisition but not at retention for preschool children, this is not what these findings imply. As argued earlier, storage and retrieval are theoretical processes, not points in time during an experiment, and both storage and retrieval processes are involved at acquisition as well as at retention. Similarly, because older, kindergarten children could benefit from intentional forgetting instructions at the time of retention does not mean that these effects are retrieval based. Before discussing any of these possibilities, however, I turn to the trace-integrity analyses in order to localize these effects in terms of the storage and retrieval processes that contribute to children's long-term retention.

Trace-Integrity Analyses

As already noted, the statistical and mathematical mechanics of this model are provided in the Appendix for the interested reader. Here the steps involved in the application of this model to the data are briefly summarized, and then the relevant findings are reported. Before the trace-integrity model can be used to interpret the impact of these manipulations on children's long-term retention, the goodness of fit of the model to the current data set must be evaluated (the machinery for these tests is shown in the Appendix). Specifically, it must be shown that the model, with only 9 parameters, does as good a job of accounting for the data as does a purely empirical model in which all 15 degrees of freedom (empirical parameters) are used in accounting for the data. The likelihood ratio tests, which are conducted for each condition and contain 6 degrees of freedom, evaluate the null hypothesis that the theoret-

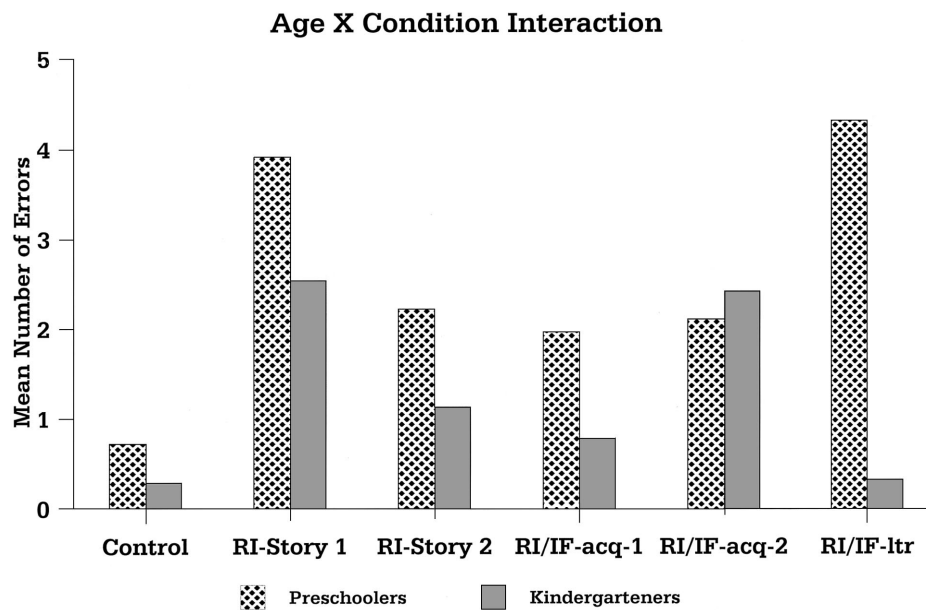


Figure 1. Mean errors for the Age \times Condition interaction. RI = retroactive interference; IF = intentional forgetting; acq = acquisition; ltr = long-term retention; RI/IF-acq-1 = RI/IF-acq_{Story 1}, and RI/IF-acq-2 = RI/IF-acq_{Story 2}.

ical model does as good a job of accounting for the data as does the empirical model. The results of the 12 tests for this experiment failed to reject the null hypothesis, indicating that the model provided an adequate fit to the retention data generated across the four conditions, all $\chi^2(6) < 10.26$.

The values of the theoretical parameters of the trace-integrity model for this experiment are presented in Table 3. In order to see whether these values differed significantly across the various conditions in this experiment, an *experimentwise* test was conducted. Like the omnibus *F* test, the experimentwise test evaluates the null hypothesis that, on average, the model's parameters did not vary between conditions. For the data in the present experiment, $\chi^2(99) = 638.73$, $p < .01$.

The next step involved a sequence of *conditionwise* tests that evaluated the null hypothesis that the numerical values of the parameters did not vary between specific pairs of conditions. In this experiment, a total of 28 conditionwise tests were needed, 6 comparisons to evaluate age effects and 11 within each age to evaluate retroactive interference and intentional forgetting effects. The numerical results of the tests to evaluate age effects (all $ps < .01$) revealed differences between preschool and kindergarten children on all lists, all $\chi^2(9) > 21.67$. The numerical results of the tests evaluating retroactive interference and intentional forgetting effects indicated that, for preschoolers, the control condition differed from all of the other conditions: control vs. RI_{Story 1}, $\chi^2(9) = 135.01$; control vs. RI_{Story 2}, $\chi^2(9) = 92.14$; control vs. RI/IF-acq_{Story 1}, $\chi^2(9) = 43.55$; control vs. RI/IF-acq_{Story 2}, $\chi^2(9) = 87.43$; and control vs. RI/IF-ltr, $\chi^2(9) = 70.83$. In addition, the RI_{Story 1} condition differed from the RI/IF-acq_{Story 1}, $\chi^2(9) = 86.94$, and the RI/IF-ltr, $\chi^2(9) = 78.29$, conditions; the two intentional forgetting conditions (RI/IF-acq_{Story 1} vs. RI/IF-ltr) differed from each other, $\chi^2(9) = 65.47$; and recall of Story 2 was different from recall of Story 1 in the RI comparison, $\chi^2(9) = 60.12$, but not

in the RI/IF-acq comparison. Finally, the two Story 2 conditions did not differ from each other.

The numerical results of these same tests for the kindergarteners showed a slightly different pattern. Specifically, as with the younger children, the control condition differed from the RI_{Story 1} condition; however, the control condition did not differ from any of the other conditions. As with the preschoolers, the RI_{Story 1} condition differed from the RI/IF-acq_{Story 1}, $\chi^2(9) = 57.65$, and the RI/IF-ltr, $\chi^2(9) = 79.98$, conditions. Unlike the case with the younger children, the two intentional forgetting conditions did not differ from each other, but as with the preschoolers, recall of Story 2 was different from recall of Story 1 only in the RI comparison, $\chi^2(9) = 42.65$, not in the RI/IF-acq comparison. Finally, the two Story 2 conditions did not differ from each other.

The last sequence of tests—namely, a sequence of *parameterwise* tests—was used to isolate the specific parameter or parameters whose estimates differed between the conditions. Each of these chi-square tests has 1 degree of freedom, and because they are tedious and space consuming to report, they are often given in summary form. Consistent with this tradition, only those parameterwise differences that were significant ($p < .05$) are reported next.

Parameterwise tests revealed that most of the age differences were localized in terms of forgetting, not reminiscence, rates, and involved both storage (parameter *S*) and retrieval (parameter *R*). It is interesting that the numerical magnitude of the age differences in storage failure rates (.09) was identical to that for retrieval failure rates (.09) when averaged across all six conditions. Although age differences were also obtained in terms of the reminiscence parameters, they did not serve to differentiate the different age groups. That is, like many previous studies in this area (for a review, see Howe & O'Sullivan, 1997), these differences did not uniformly favor one age group over another.

Table 3
Parameter Estimates

Age and condition	<i>S</i>	<i>R</i>	<i>a</i>	<i>r</i> ₁	<i>r</i> ₂	<i>r</i> ₃	<i>f</i> ₁	<i>f</i> ₂	<i>f</i> ₃
Preschoolers									
Control	.11	.00	.06	.95	.98	.99	.62	1.0	.94
Retroactive interference (RI)									
Story 1	.22	.19	.04	.79	.99	1.0	.26	.60	.60
Story 2	.13	.12	.00	.97	1.0	1.0	.68	.80	.97
RI/intentional forgetting at acquisition									
Story 1	.09	.23	.06	.97	.99	1.0	.62	.85	.89
Story 2	.05	.15	.11	.90	1.0	1.0	.30	.46	.80
RI/intentional forgetting at retention									
Story 1 (only)	.30	.18	.02	.87	.94	1.0	.52	.98	.35
Kindergarteners									
Control	.05	.06	.01	.99	1.0	1.0	.66	.90	.54
Retroactive interference (RI)									
Story 1	.24	.00	.02	.93	1.0	1.0	.62	.89	.50
Story 2	.00	.08	.00	.99	1.0	.99	.69	.80	.33
RI/intentional forgetting at acquisition									
Story 1	.03	.05	.00	.98	1.0	1.0	.80	.49	.97
Story 2	.00	.14	.00	.98	1.0	1.0	.83	.60	.90
RI/intentional forgetting at retention									
Story 1 (only)	.03	.02	.00	1.0	1.0	1.0	.95	.60	.90

Concerning retroactive interference effects, the locus of parameterwise differences between the control and RI conditions was primarily in terms of forgetting. For the younger children, these effects manifested themselves both in terms of storage-based forgetting (S) and retrieval-based forgetting (R), whereas for the older children they were purely storage-based effects. Moreover, age differences emerged in reminiscence patterns because of retroactive interference effects for preschoolers but not kindergarteners, and these age differences were confined to retrieval-mediated trace recovery. That is, the probability of two consecutive successes (as measured by r_1) and the probability of successes following consecutive errors (as measured by the f_i) were lower in the RI conditions than in the control condition for the preschoolers, but no differences emerged for the kindergarteners. Thus, for younger children, retroactive interference increased both storage- and retrieval-based forgetting rates over the retention interval and decreased the probability of retrieval-based trace reminiscence across test opportunities during the retention session. For the older, kindergarten children, these effects were less widespread, being restricted to storage failures.

Release from retroactive interference that was due to the intentional forgetting manipulation also exhibited qualitative age differences in the pattern of parameter variation. As also shown by the ANCOVA-based findings, the intentional forgetting manipulation was effective only when administered at acquisition for the preschoolers, but it was effective at eliminating retroactive interference when manipulated at acquisition and retention for the kindergarten children. The important finding is that the locus of this effect was at storage regardless of age—that is, the probability of storage-based forgetting declined significantly between the RI/IF-acq_{Story 1} and RI_{Story 1} conditions regardless of age and between the RI/IF-ltr and RI_{Story 1} conditions for the kindergarten children only. In fact, in all cases, the intentional forgetting instruction reduced the extent of storage failures to the level in the control condition. No effects were observed for retrieval failures. It is interesting that this same manipulation produced a marked elevation in retrieval-based trace reminiscence for the preschoolers, one that brought levels back to the level in the control condition (in particular, the parameters r_1 and f_i).

Finally, Story 2 effects were localized in forgetting and were restricted to storage failures. Specifically, the parameter estimates for Story 2 recall were much like those for the control group and reflected lower storage failure rates than for Story 1 in the RI conditions regardless of age. No differences were obtained between Story 1 and Story 2 in the intentional forgetting conditions (RI/IF-acq), and no differences were obtained between the RI and RI/IF-acq conditions in Story 2 recall.

Summary

To summarize, the results of both the ANCOVA and the trace-integrity analyses indicated that, consistent with previous findings (Howe, 1995), preschool and kindergarten children experience considerable retroactive interference. Unlike in a previous study (Howe, 1995), where primarily storage-based forgetting differences were found, the effects obtained here involved both storage and retrieval components of forgetting as well as some retrieval-based reminiscence effects, at least for the preschoolers. Although this may be due simply to subject sampling, it may have more to

do with changes in the material being memorized. That is, in the previous study (Howe, 1995), children learned lists of paired associates or pictures, whereas here they learned more integrated stories. Perhaps because the present material was better integrated, both storage and retrieval components of forgetting contributed to retention performance, particularly for the younger participants. In any event, there is consensus (a) that strong retroactive interference effects exist in preschool and kindergarten children's retention of picture lists as well as stories, contrary to the early findings of Koppenaal et al. (1964), and (b) that the primary locus of these effects is at forgetting, particularly storage-based failures.

In addition to the replication and extension of findings concerning the locus of retroactive interference effects in preschool children's long-term retention, one of the most important findings to emerge from this experiment concerns the existence and locus of intentional forgetting effects. Here, again, the ANCOVA and trace-integrity analyses complemented each other and showed that the intentional forgetting instruction was effective for the preschoolers only when administered immediately following acquisition but was effective for the kindergarteners even when administered at the time of retention testing. The trace-integrity model confirmed that these effects were due primarily to a release from storage-based forgetting. As storage-based forgetting is a primary site of retroactive interference effects, it is more than coincidental that it is also the locus of the intentional forgetting manipulation's release from interference effects.

Discussion

There were four objectives in the current experiment: (a) to establish the presence and locus of retroactive interference effects in preschool and kindergarten children's retention of highly integrated material, (b) to demonstrate intentional forgetting effects in these children, (c) to determine whether intentional forgetting instructions reduce interference effects, and (d) to determine the fate of the to-be-forgotten information in memory. Concerning the first objective, this experiment showed that 4- and 6-year-olds were as susceptible to retroactive interference effects when learning well-integrated stories as when learning paired associates (e.g., Howe, 1995). Although the primary locus of these effects was at forgetting, particularly storage-based forgetting, retrieval failures and reminiscence were also evident among the preschool children. That more of the basic memory processes are affected by retroactive interference in younger children than in older children is not unanticipated (Howe, 1995; Howe & O'Sullivan, 1997) and does not undermine the growing consensus that retroactive interference effects (a) are robust in preschool children, contrary to some earlier reports (Koppenaal et al., 1964); (b) are localized mainly in forgetting; and (c) involve changes to information at the level of storage.

The second and third objectives of this experiment considered together provided important and provocative findings that would not have been predicted directly from the extant literature on intentional forgetting in children. Specifically, 4- and 6-year-old children showed not only that they were responsive to instructions to forget a story that they had just learned but also that once having forgotten it they were released from the retroactive interference shown by children who were not instructed to forget the interfering story. It is particularly significant that the younger children were

able to use intentional forgetting to ameliorate interference effects (although only when instructed at acquisition), because evidence from a variety of sources indicates that not until 6 or 7 years of age is children's cognitive inhibition sufficiently mature to support intentional forgetting (e.g., see S. P. Wilson & Kipp, 1998). An important related finding was that the locus of the intentional forgetting effects was at storage. That is, intentional forgetting reduced retroactive interference primarily by altering the pattern of storage failures. It is more than coincidental that storage was also a primary locus of retroactive interference effects and that even preschoolers were able to alter information so it did not interfere with the to-be-remembered information. This finding is consistent with the more general observation that maintaining information in storage is critical to the development of children's long-term retention (Howe & O'Sullivan, 1997), though it is inconsistent with current theory that favors the later onset of cognitive inhibition mechanisms, at which time the impact is at the level of retrieval (e.g., S. P. Wilson & Kipp, 1998).

There are two ways to interpret these discrepant findings, both of which potentially provide viable accounts of much of the data. First, it may be that preschool children have sufficiently mature inhibitory mechanisms or processes to suppress verbal information as a result of instructions to forget, because they wish to keep a secret, or because they intend to deceive. Accordingly, their ability to inhibit information has traditionally been underestimated, perhaps masked by performance difficulties with the standard experimental tasks that not only require response suppression but make significant demands on children's developing information-processing skills (e.g., attention, selective search, selective rehearsal). Indeed, when tasks are simplified to require response suppression alone, young preschoolers can keep secrets and inhibit truthful responses in the service of deception (e.g., Lewis et al., 1989; Pipe & Wilson, 1994). This example illustrates the need for developmentalists to provide what Haith (1993) referred to as models of partial accomplishment in which children are not seen as either "having" or "not having" a particular cognitive ability and in which truly developmental characterizations of how these skills gradually unfold are provided (see also Fischer & Bidell, 1991). The research reported here is a step in this direction in the domain of children's intentional forgetting.

The second approach to interpreting the findings is to search for a mechanism other than cognitive inhibition that would account for young children's use of intentional forgetting and the observed reduction in storage failure at long-term retention. One likely candidate for this mechanism is the reorganization of information in storage so that the to-be-remembered information is segregated and made distinct from the to-be-forgotten information (e.g., see Howe et al., 2000). For example, in the present study, because the two stories had considerable internal cohesion ("within-list" similarity) and shared many features ("between-list" similarity), interference effects might predictably be strong. If confusion between traces is to be avoided, cross-talk or interference among traces needs to be eliminated. Because memorability treads a fine line between similarity and distinctiveness, the intentional forgetting manipulation may have aided the latter by providing a salient dimension that served to discriminate traces in storage (e.g., see Hunt & McDaniel, 1993). That intentional forgetting effects were mainly seen at storage is important because it suggests that identifying one story as "to be forgotten" and one as "to be remem-

bered" did not simply result in editing information at output but rather led to the reorganization of information in storage, altering it in memory. The notion of distinctiveness in storage is a familiar one in the adult literature on intentional forgetting, where it is referred to as *segregation*, a process that has been strongly linked to enhanced recall on a variety of tasks (see MacLeod, 1998).

An interesting developmental finding that emerged was that retroactive interference was reduced for preschoolers only when intentional forgetting instructions were provided following acquisition and not when they were administered just prior to retention testing 24 hrs after acquisition. In contrast, kindergarten children were able to utilize intentional forgetting to reduce retroactive interference regardless of when it was manipulated. This pattern of findings has also been obtained elsewhere, albeit with a more complex semantic manipulation and older children (second and fourth graders; Howe, 2002). What these results might mean developmentally is that older children are more flexible in using recently encoded information to reorganize information already "galvanized" in storage through consolidation processes. A wealth of other outcomes have shown that older children are more flexible manipulators of information in storage than are younger children, especially when it comes to long-term retention (for reviews, see Howe, 2000, and Howe & O'Sullivan, 1997).

The fourth objective of this research concerned the fate of the to-be-forgotten information in memory. Consistent with the findings from other intentional forgetting studies, the to-be-forgotten material in the present experiment was recalled as well as the to-be-remembered information regardless of whether children were provided with intentional forgetting instructions at acquisition. Indeed the children in the retroactive interference conditions were able to recall Story 2 as well as the children in the control group could recall Story 1. Clearly, the to-be-forgotten information was as available and accessible in memory when it was supposedly to be forgotten, and thus not interfering with recall, as it was without forgetting instructions, when it did interfere with recall.

More generally, that intentional forgetting instructions did not produce forgetting has several interesting implications for eyewitness memory and some of the processes that may underlie it. For example, it may be that explicitly instructing children to forget can actually have a memory-preserving function on eyewitness recall. That is, instructions to forget may keep the to-be-forgotten memories more intact than would otherwise be the case because, as already noted, such instructions can lead to trace reorganization and greater distinctiveness in memory. This, in turn, reduces the likelihood of interference among memories and hence, the likelihood that such memories will be forgotten.

It is interesting, then, that trying to suppress or forget an event, whether it is traumatic or not, may actually improve one's memory for the event rather than eliminate it. This, of course, bodes poorly for those who use this strategy to try to forget emotionally charged experiences and leads to the hypothesis that those who profess to have tried to forget such experiences may actually have better memory for them than those who have not tried such approaches to forgetting. Even individuals who have histories of trauma (and who might be highly motivated to forget) are not always better at directed forgetting or thought suppression. For example, Cloitre, Cancienne, Brodsky, Dulit, and Perry (1996) found no differences in directed forgetting rates between women with and without histories of abuse, although those with abuse histories did perform

better on the to-be-remembered words. Similar findings have been reported for women with and without abuse histories and with and without posttraumatic stress disorder (PTSD). That is, although women with PTSD did not remember as many of the nontraumatic words as did women without PTSD, there were no differences in directed forgetting rates (McNally, Metzger, Lasko, Clancy, & Pitman, 1998). Clearly, instructions to suppress or forget information do not lead to its elimination from memory among individuals either motivated or unmotivated to forget or among adults or children. As shown in this study, intentional forgetting can produce better memory for the to-be-forgotten materials even in preschool children.

In conclusion, this study establishes that retroactive interference effects are robust in preschool and kindergarten children and that these effects are most frequently evidenced in increases in storage-based forgetting. In terms of intentional forgetting, the results are clear that even young, preschool children can benefit from instructions to forget and that these effects are most often observed in reductions of storage-based forgetting. That children so young can benefit from instructions to forget is not easily reconciled with claims that intentional forgetting is the result of cognitive inhibitory processes that emerge during the school years. These findings are also inconsistent with theories in which the locus of intentional forgetting is said to be at retrieval. In their entirety, the findings reported here are more suggestive of the conclusion that intentional forgetting instructions produce traces that are better discriminated in storage. The general implication for eyewitness memory is that instructions to forget can reduce misinformation arising from retroactive interference as long as both the original information and subsequent information are kept distinct and, for very young children, closely associated in time.

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Appendix

Mechanics of the Trace-Integrity Model

The parameters from Table 1 in the text are mapped onto the outcome space of a four-trial retention experiment in Table A1. It is this mapping that provides for the lawful extraction of information about storage and retrieval processes from observable outcomes on test trials. That is, it is this set of equations that states explicitly what the relationship is between the outcomes of an experiment and the underlying or latent memory and cognitive processes that determine these outcomes (also see Batchelder & Riefer, 1999). A detailed description of how these parameters are linked to the data, the basis for the interpretation of the parameters, the history of the model, as well as the utility of this approach when exploring developmental differences in retention are provided in a recent review by Howe and O'Sullivan (1997).

The purpose of this Appendix is to show the statistical machinery used to evaluate the model's goodness of fit to the observations and the procedures used to evaluate hypotheses about theoretical processes. It is paramount that before the trace-integrity model is used to interpret the impact of any manipulation on the theoretical processes measured in this framework, the goodness of fit of the model to the data must be evaluated, and numerical estimates of the parameters must be obtained. Fortunately, a well-defined set of procedures is available for these purposes (see Howe, 1991, 1995; Howe & Brainerd, 1989; Howe, Courage, & Bryant-Brown, 1993). The process involves the five-step sequence outlined next.

The first two steps involve translating the data space into a probability space, which is subsequently transformed into a mathematical space. With the use of maximum likelihood theory, the first transformation results in a function that expresses the a posteriori likelihood of any data sample. The present function has 15 degrees of freedom and takes the form

$$L_{15} = \{p[C_1C_2C_3C_4]^{M[CCCC]} \times p[C_1C_2C_3E_4]^{M[CCCE]} \times \dots \times p[E_1E_2E_3C_4]^{M[EEEC]} \times p[E_1E_2E_3E_4]^{M[EEEE]}\}. \quad (A1)$$

The second transformation permits derivation of the theoretical likelihood, something that is accomplished by simply substituting the equations

in Table A1 (denoted in Equation A2 by the term h) for the 16 terms in Equation A1. This yields a function with 9 degrees of freedom (since the 16 expressions are based on only 9 parameters) and takes the form

$$L_9 = \{h(p[C_1C_2C_3C_4]^{M[CCCC]} \times h(p[C_1C_2C_3E_4]^{M[CCCE]} \times \dots \times h(p[E_1E_2E_3C_4]^{M[EEEC]} \times h(p[E_1E_2E_3E_4]^{M[EEEE]})\}. \quad (A2)$$

The third step consists of counting the number of times each of the 16 events occurred in the sample data (i.e., summing across both subjects and items within each condition of interest), inserting these numbers in the relevant exponents in Equation A2, and maximizing the function using a standard computer optimization routine (e.g., SIMPLEX). The optimal solution yields numerical estimates of the model's nine parameters as well as the value of the likelihood function L_9 . This latter value (which is more commonly estimated using the log transform $-2\ln L_9$) is used to evaluate the model's goodness of fit (the fourth step) and to examine hypotheses about between- and within-condition differences in the numerical estimates of parameters (the fifth step).

The fourth step involves evaluating the fit of the model to the data. This is accomplished by maximizing (using the same log transform as above) Equation A1 for the same data as Equation A2, which yields an estimate of the likelihood of the data before the model was imposed (i.e., with all empirical probabilities free to vary, L_{15}). Because Equation A1 exhausts all of the information in the data, the value of L_{15} will always be the maximum likelihood for that data set. Because the trace-integrity model does not exhaust this information (having only 9 degrees of freedom, not 15), the estimated likelihood of Equation A2 will tend to be smaller. Goodness of fit is assessed using likelihood ratio tests that determine whether or not this difference is statistically reliable. Specifically, this test takes the form

$$\chi^2(6) = (-2\ln L_9) - (-2\ln L_{15}) \quad (A3)$$

and evaluates the null hypothesis that the trace-integrity model fits the data.

Finally, the fifth step involves testing hypotheses about the theoretical processes underlying retention performance as reflected in the numerical

Table A1
Mathematical Expressions Defining the Empirical Outcome Space

Outcome	Expression
$p(\text{CCCC})$	$(1 - S)(1 - R)r_1r_2r_3$
$p(\text{CCCE})$	$(1 - S)(1 - R)r_1r_2(1 - r_3)$
$p(\text{CCEC})$	$(1 - S)(1 - R)r_1(1 - r_2)f_1$
$p(\text{CECC})$	$(1 - S)(1 - R)(1 - r_1)f_1r_1$
$p(\text{ECCC})$	$Sa(1 - R)r_1r_2 + (1 - S)Rf_1r_1r_2$
$p(\text{CCEE})$	$(1 - S)(1 - R)r_1(1 - r_2)(1 - f_1)$
$p(\text{CECE})$	$(1 - S)(1 - R)(1 - r_1)f_1(1 - r_1)$
$p(\text{ECCE})$	$Sa(1 - R)r_1(1 - r_2) + (1 - S)Rf_1r_1(1 - r_2)$
$p(\text{CEEC})$	$(1 - S)(1 - R)(1 - r_1)(1 - f_1)f_2$
$p(\text{ECEC})$	$Sa(1 - R)(1 - r_1)f_1 + (1 - S)Rf_1(1 - r_1)f_1$
$p(\text{EECC})$	$S(1 - a)a(1 - R)r_1 + SaRf_1r_1 + (1 - S)R(1 - f_1)f_2r_1$
$p(\text{EECE})$	$(1 - S)(1 - R)(1 - r_1)(1 - f_1)(1 - f_2)$
$p(\text{EEEC})$	$Sa(1 - R)(1 - r_1)(1 - f_1) + (1 - S)Rf_1(1 - r_1)(1 - f_1)$
$p(\text{EEEE})$	$S(1 - a)a(1 - R)(1 - r_1) + SaRf_1(1 - r_1) + (1 - S)R(1 - f_1)f_2(1 - r_1)$
$p(\text{EEEC})$	$S(1 - a)^2a(1 - R) + S(1 - a)aRf_1 + SaR(1 - f_1)f_2 + (1 - S)R(1 - f_1)(1 - f_2)f_3$
$p(\text{EEEE})$	$S(1 - a)^3 + S(1 - a)^2aR + S(1 - a)aR(1 - f_1) + SaR(1 - f_1)(1 - f_2) + (1 - S)R(1 - f_1)(1 - f_2)(1 - f_3)$

Note. C = correct response; E = incorrect response. Each probability in the left column appears in the empirical likelihood function. In the likelihood function for the trace-integrity model, these probabilities are replaced by the corresponding expression in the right column.

estimates of the model's parameters. Because these parameters are identifiable (see Howe & Brainerd, 1989), they can be used in direct tests of hypotheses concerning between-condition and within-condition differences in the rates of forgetting and reminiscence as well as the storage and retrieval loci of these differences. The statistical process for testing hypotheses is straightforward, involving a series of likelihood-ratio chi-square tests known as an *experimentwise* test, *conditionwise* tests, and *parameterwise* tests. The experimentwise test, like the omnibus F test, evaluates the null hypothesis that, on average, the model's parameters do not vary between conditions. The exact test is given by

$$\chi^2[k \times (9) - 9] = [(-2\ln L_{9i}) + (-2\ln L_{9i+1}) + \dots + (-2\ln L_{9k})] - (-2\ln L_{9\text{pooled}}), \quad (\text{A4})$$

where the first term represents the summation of the $-2\ln L_{9i}$ values for each of the i through k individual conditions in the experiment and the last term represents the single $-2\ln L_{9}$ likelihood value found by pooling the data from all k conditions. Because there are 9 degrees of freedom involved in each of the k terms in the first part of the expression, the asymptotic chi-square distribution of the experimentwise test has $k \times (9) - 9$ degrees of freedom.

The conditionwise test, like the t test, evaluates the null hypothesis that, on average, the model's parameters do not vary between specific pairs of conditions. The exact test is given by

$$\chi^2(9) = [(-2\ln L_{9i}) + (-2\ln L_{9j})] - (-2\ln L_{9ij}), \quad (\text{A5})$$

where the first term represents the summation of the $-2\ln L_{9i}$ values for conditions i and j and the final term represents the single $-2\ln L_{9}$ value found by pooling the data for the ij conditions. Because there are always 18

degrees of freedom associated with the first term and 9 degrees of freedom for the last term, the asymptotic chi-square distribution of the conditionwise test has 9 degrees of freedom.

For those pairs of conditions that differ, the parameterwise test evaluates the null hypothesis that the numerical estimate of a particular parameter does not vary between those two conditions. The exact test is given by

$$\chi^2(1) = [(-2\ln L_{9i}) + (-2\ln L_{9j})] - [(-2\ln L'_{9i}) + (-2\ln L'_{9j})], \quad (\text{A6})$$

where the first term is the same as in Equation A5 and the second term represents the joint likelihood of the data from the two conditions (i.e., minimizing L'_{9i} and L'_{9j} simultaneously) subject to the single restriction that the parameter being tested (e.g., S) must assume the same value in the two conditions. This restriction results in an asymptotic test statistic of $\chi^2(1)$.

Finally, there are two types of within-condition hypotheses that can be evaluated: namely, numerical equivalences (e.g., $a = 0$; $S = R = .1$; $r_1 = r_2 = 1.0$) and algebraic relationships (e.g., $S > R$; $r_1 < r_3$). Both types of hypotheses can be tested using the single statistic

$$\chi^2(1) = (-2\ln L_{9i}) - (-2\ln L_{8i}), \quad (\text{A7})$$

where the first term is simply the likelihood value associated with condition i when all of the parameters are free to vary and the last term represents the same condition with a single restriction imposed. Like the between-condition parameterwise test, this chi-square test has 1 degree of freedom.

Received June 20, 2000

Revision received June 25, 2001

Accepted June 28, 2001 ■