Interference in Memory Development

The cost of learning:

Interference effects in memory development

THESIS

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Abstract

Learning often affects future learning and memory for previously learned information by exerting either facilitation or interference effects. This work focuses on interference effects with the goal of better understanding memory development and mechanisms of such interference. In this study preschool-aged children and adults participated in a three-phased associative learning paradigm containing stimuli that were either unique or repeated across phases. Both age groups demonstrated interference effects, but only for repeated items. Proactive effects were comparable across age groups, whereas retroactive interference was much stronger in children. Retroactive interference increased in adults when contextual differences between phases were minimized (Experiment 2), and decreased in adults who were more successful at encoding repeated pairs of stimuli (Experiment 3). Together, these results suggest that configural encoding of stimuli may be an important mechanism of memory retention and memory development.
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INTRODUCTION

This research focuses on interactions between learning and memory with the goal of understanding how memory develops. Prior work suggests that learning and memory do interact, in that previously acquired knowledge affects acquisition of new knowledge (Krascum & Andrews, 1998; Murphy & Allopenna, 1994) and newly acquired knowledge affects memory for previous knowledge (Roediger & Marsh, 2005).

In some cases this interaction is facilitative. For example, expertise in a particular domain often benefits memory for information within that domain (Chi, Glaser, & Rees, 1982; Guida, Gobet, Tardieu, & Nicolas, 2012). Previous knowledge may also assist category learning (Murphy & Allopenna, 1994) and learning of causal relations (Griffiths, Sobel, Tenenbaum, & Gopnik, 2011). Similarly, seminal work by Ebbinghaus demonstrated savings effects, in which unconscious memory for previous learning facilitates later learning of the same information (Nelson, 1985). And finally, recalling previously learned information during multiple-choice tests may affect retention of this information (Roediger & Karpicke, 2006; Roediger & Marsh, 2005).

At the same time, interactions between learning and memory can also produce interference effects: under some conditions, memory for previously learned information attenuates learning of new information (i.e., proactive interference, or PI), whereas under other conditions, learning of new information attenuates memory for previously learned information (i.e., retroactive interference, or RI). For example, a professor may
experience PI when finding it difficult to learn students’ names at the beginning of each semester, as they have taught many students previously. At the same time, RI may affect the professor’s ability to recall the name of a particular student from a previous semester, as they have since learned the names of other students. Interference effects may be relatively benign, as in these examples, but may also produce substantial detriments to learning systems.

Researchers have studied interference effects experimentally for over a century, producing a wealth of theories and insights into the cognitive and neural processes of learning and memory (Anderson & Neely, 1996; Wixted, 2004). Traditionally, resistance to PI has been related to the integrity of executive function served by prefrontal cortex (see Anderson & Bjork, 1994; Jonides & Nee, 2006, for reviews), whereas resistance to RI has been related to the integrity of memory traces served by the hippocampal system (see Wixted, 2004, for a review; but see Anderson & Bjork, 1994). If this is true, interference paradigms can be used to establish mappings between aspects of memory and the underlying brain structures in order to better understand how memory develops. We will return to this issue in the section on memory development.

A standard way of experimentally examining PI and RI effects would be to present a learning task X (e.g., Study List 1) followed by a learning task Y (e.g., Study List 2). Attenuation of learning on task Y that is not attributable to fatigue or other non-memory factors is considered to stem from PI (see Anderson & Bjork, 1994; Anderson & Neely, 1996; Jonides & Nee, 2006; Kail, 2002, for reviews). Similarly, attenuation of memory for information presented in task X following task Y (assuming that attenuation is not attributable to fatigue or other non-memory factors) is considered to stem from RI (see
A model paradigm used to investigate interference is the paired-associates learning task, in which participants study lists of arbitrarily paired items, such as bag-tree (which can be presented either as words or as pictures). Researchers often refer to these lists in abstract notation, such as AB, indicating the association between a cue (A) and a target (B). After learning the AB list, participants learn a second list of pairs before memory for both lists is tested. The second list can involve completely new pairs (AB-CD), cues from the first list paired with novel items (AB-AC), or items from the first list that are paired differently (AB-ABr).

During testing, participants are generally presented with a cue from a particular pairing and are asked to identify the associated target. PI is identified as attenuated memory for targets from the second list, and RI is identified as attenuated memory for targets from the first list followed learning of the second list. Memory performance is compared to baseline conditions in which participants learn the first list but not the second (controlling for RI), or learn the second list but not the first (controlling for PI). Typically, AB-AC and AB-ABr lists generate the greatest amount of interference and these are the most commonly used list types for the study of these effects.

Although early studies of interference effects greatly contributed to our understanding of memory by implementing the paired-associates paradigm, this work has been criticized for focusing on list memory and thus representing a narrow set of memory phenomena (see Dempster & Corkill, 1999, for a review). Later research has indicated the ubiquity of interference effects in learning and memory. These effects have transpired across a wide range of populations and tasks and profoundly affected our understanding of learning and memory. For example, PI and RI have been documented in early development using a
variety of tasks (Fagan, 1977; Howe, 1995; Lee & Bussey, 2001; Mareschal, Quinn, & French, 2002; Rossi-George & Rovee-Collier, 1999; Tyrrell, Snowman, Beier, & Blanck, 1990). Although forgetting, or errors of omission, is among the most studied consequences of PI and RI, infants and young children exhibit remarkable susceptibility to perseveration-based PI in the A-not-B task (Diamond, 1985; Piaget, 1963) and the Dimensional Change Card Sort test (DCCS; Zelazo, 2006). Other consequences of interference may include memory intrusions, resulting in false memories (see Brainerd & Reyna, 2002, for an extensive description of various false memory phenomena).

Interference effects can also attenuate transfer of learning: one recent study (Opfer & Thompson, 2008) found that previous work reporting a surprising lack of transfer of children’s representation of numerical magnitude may actually have been due to the presence of PI effects.

Finally, interference effects have affected our understanding of learning and memory in some unexpected ways. For example, although people typically experience only partial forgetting of information due to interference, early connectionist models exhibited catastrophic RI, in which new learning produced almost complete forgetting of previously learned information (McCloskey & Cohen, 1989; Ratcliff, 1990). Such dramatic (and unexpected) memory failures of the early connectionist systems resulted in proposals of complementary learning systems, one sub-served by the hippocampus and one by the neocortex (McClelland, McNaughton, & O’Reilly, 1995). Implementing this complementary learning systems approach in connectionist models resulted in substantially attenuated interference effects (McClelland et al., 1995; Norman & O’Reilly, 2003). Clearly, interference effects have profoundly affected our understanding
of learning, memory, and cognitive development. In what follows, we review major findings and the proposed mechanisms of both kinds of interference.

**Mechanisms of PI**

PI has been traditionally linked to executive functioning, including attention, working memory, and cognitive flexibility, and thus to the integrity of the prefrontal cortex (see Jonides & Nee, 2006 for a review). For example, Engle and colleagues (Engle, 2002; Kane & Engle, 2000) demonstrated that resistance to PI depends on working memory span, with participants with low spans exhibiting greater interference effects than participants with higher spans.

There is also a large body of developmental research linking PI with cognitive flexibility. In these tasks, infants and young children learn to respond to a set of stimuli in a particular way. Later, these contingencies change, such that success in the task requires flexible switching. Many infants and children continue to respond to the stimuli in the way required by the first set of contingencies. Infants, for example, demonstrate perseveration in the A-not-B task by continuing to search for an attractive object where it had been hidden previously, despite watching the experimenter hide the object in a new location (Diamond, 1985; Piaget, 1963). Older children also demonstrate perseveration in the Dimensional Change Card Sort test (DCCS; Zelazo, 2006), by failing to follow instructions to switch to a new dimension (e.g., shape) and continuing to sort objects according to a previously relevant dimension (e.g., color). Many children perseverate even when aware of the new sorting dimension (Munakata & Yerys, 2001; Zelazo, Frye, & Rapus, 1996). The similarities between these phenomena and PI effects found in adults
are striking, in that infants and children learn one set of contingencies and have difficulty learning a second set.

Failures of executive functioning giving rise to PI effects led researchers to link PI with the integrity of prefrontal cortex. These links have been confirmed in patient studies (e.g. Shimamura, Jurica, Mangels, Gershberg, & Knight, 1995) as well as in neuroimaging studies (e.g. Jonides & Nee, 2006). In particular, Shimamura et al. (1995) demonstrated that patients with lesions to the prefrontal cortex experience stronger PI on an AB-AC task than control participants.

Therefore, there is little surprise that one of the most prominent theories of the cognitive mechanisms of interference (Anderson, 2003; Anderson & Bjork, 1994; Anderson, Bjork, & Bjork, 1994; Anderson & Neely, 1996; Anderson & Spellman, 1995) links PI to an important aspect of executive function – inhibitory processes. Consider the AB-AC paradigm: when cue A is presented during learning of the second list, it activates a previously learned, prepotent association with B, thus requiring the learner to actively inhibit this response in favor of C. Failure to inhibit B results in PI. However, inhibition is not cost-free: success at inhibiting B allows learning of C, but may result in forgetting of B, thus potentially giving rise to RI.

Mechanisms of RI

One way of explaining RI is through inhibitory processes, as discussed above. The idea is that if cues in two lists overlap (as in AB-AC lists), then learning of the AC pairing in the second list requires inhibiting the learned response B. This inhibition results in RI – forgetting of the original AB pairing. In contrast, failure to inhibit B results in PI, with little or no RI.
Evidence for this framework has been found in adults using the retrieval practice paradigm (Anderson et al., 1994). In this paradigm, participants study a list of category-exemplar word pairs (e.g., Fruits-Orange), in which multiple items come from the same category. Participants then practice retrieving only a subset of these items before being tested on all pairs. The primary finding is that practice results in higher accuracy for practiced pairs, but lower accuracy for unpracticed pairs from the same category, relative to pairs from categories that were not practiced at all. This suggests that retrieval of the practiced pairs inhibits memory for unpracticed exemplars within the same category (Anderson, 2003).

Several predictions can be inferred from this account. First, proactive and retroactive interference share the same mechanism and these types of interference should be inversely related: weaker PI stems from more efficient inhibition, which leads to stronger RI. And second, participants with less capacity to inhibit (i.e., young children, low working memory span adults, or patients with prefrontal lesions) should exhibit stronger proactive and weaker retroactive interference than typical adults.

Another account of interference suggests that RI arises when new learning disrupts the consolidation process, in which memories gradually migrate from the hippocampus to cortical regions (Dewar, Cown, & Della Sala, 2007; McClelland et al., 1995; Wixted, 2004). Importantly, according to some accounts, new learning need not be similar to previously stored memories in order to induce RI, as any hippocampal activity attenuates memory for recently learned information still contained in the hippocampus (Wixted, 2004). This theory is supported by findings that adults are less likely to experience RI for a set of information (e.g., set A) when hippocampal activity is minimized following
learning. Specifically, RI may be reduced when adults sleep (Abel & Bäuml, 2013; Ekstrand, 1972) or consume alcohol (Mann, Cho-Young, & Vogel-Sprott, 1984) or benzodiazepines (Coenen & van Luijtelaar, 1997) following initial learning of set A. Some work suggests that RI may also be reduced with increased delays (and as a result greater opportunity for consolidation) between learning and testing (MacLeod & Macrae, 2001; see Wixted, 2004, for a review).

Another (albeit indirect) source of support for the consolidation account is catastrophic interference. Recall that early connectionist models of learning and memory exhibited a dramatic case of RI – catastrophic forgetting of previously learned items after learning new information (McCloskey & Cohen, 1989; Ratcliff, 1990) – and that this catastrophic interference may be avoided through consolidation (McClelland et al., 1995). Connectionist models employing a computational equivalent of consolidation successfully avoided catastrophic interference (McClelland et al., 1995; Norman & O’Reilly, 2003), suggesting that consolidation may play an important role in reducing vulnerability to RI.

Importantly, in contrast to the inhibition theory linking interference to prefrontal functioning, this theory links interference to the functioning of the hippocampal system. In addition, as any hippocampal activation disrupts consolidation, this account predicts that the magnitude of RI should not be affected by similarity between learning sets (Wixted, 2004).

Whereas the former two theories attribute interference effects to aspects of retrieval or consolidation, the third theory suggests that aspects of initial encoding may help determine the extent of RI effects (Humphreys, Bain, & Pike, 1989; O’Reilly & Rudy,
2001; Sutherland & Rudy, 1989). According to this account, memories are protected from interference when they are encoded in a complex configural structure, such as between a cue, target, and context (Humphreys et al., 1989). For example, a professor may avoid forgetting the name of a student by associating not only the student with the name, but also the context of the classroom and semester in which the student was taught. The encoding of more complex structures may be effective at reducing interference because it introduces unique information which reduces the amount of overlap between learning sets (Humphreys et al., 1989).

Developmental work has suggested that young children have difficulty encoding complex structures of associations (Rudy, Keith, & Georgen, 1993). One recent study (Yim, Dennis, & Sloutsky, 2013) investigated the development of episodic memory with a modified paired-associates task in which objects were paired together as a cue and target in different contexts. Crucially, the structure of the stimulus pairings was manipulated, such that high performance required differing levels of associative complexity across conditions. For example, in one condition successful learning could be achieved by merely encoding a single two-way (cue-target) association for each pair, while in other conditions participants were required to learn multiple two-way associations or a three-way (cue-target-context) association. In addition to providing behavioral data Yim et al. (2013) applied a Multinomial Processing Tree model to the results and concluded that the ability to form more complex associative structures increases between ages 5 years and adulthood. In sum, this account makes two critical predictions: it implicates configural encoding in preventing RI and suggests that RI
should be greater in children and individuals who are less proficient at configural encoding.

*Interference and Memory Development*

The processes by which learning and memory interact are especially important for understanding memory development. Intuitively learning and memory interact in many essential aspects of cognitive development, including categorization, reading, and language learning. These processes have the potential to produce substantial interference effects, as children learn that the same objects can be categorized in different ways, that the same words can be read in different sentences, and that the same concepts can be mapped onto different labels.

The current work aims to use interference to better understand the development of episodic memory. Many believe that episodic memory exhibits a relatively late onset and undergoes protracted development, especially compared to the rapid development of semantic memory (Drummey & Newcombe, 2002; but see Bauer, et al, 2000). However, even those who argue for an early onset acknowledge that throughout the preschool years many aspects of episodic memory are fragile. Although sometimes young children exhibit excellent memory for individual items (Sloutsky & Fisher, 2004), they have difficulty remembering what happened, where and when (Bauer, 2007). Children’s testimonies in forensic contexts are often unreliable (Pipe & Salmon, 2009), and laboratory recall/recognition tasks demonstrate that episodic memory continues to improve through adolescence (Brainerd, Reyna, & Ceci, 2008; Ghetti & Lee, 2011).
If episodic memory does undergo protracted development (Sluzenski, Newcombe, & Kovacs, 2006; Sluzenski, Newcombe, & Ottinger, 2004), what causes this change? And how does this change in memory relate to neural development?

Developmental changes have been linked to increased memory capacity (Kail, 1990), use of memory strategies (Schneider, Kron, Hünnerkopf, & Krajewski, 2004), encoding and retrieval efficiency (Knott, Howe, Wimmer, & Dewhurst, 2011; Sluzenski et al., 2006), and formation of complex (configural) memory structures (Yim et al., 2013). However, these findings do not uniquely identify neural changes subserving memory development, and these changes are a matter of considerable debate. Some argue that there is significant maturation of the PFC even after adolescence (Gogtay et al., 2006; Sowell et al., 2004), while there are relatively small changes in the hippocampus after the age of four, which suggests that the PFC is the primary source of change past infancy. Alternatively, studies focusing on the hippocampus report that structures, such as the posterior parahippocampal gyrus, play a substantial role in memory development (Ghetti, DeMaster, Yonelinas, & Bunge, 2010).

Work reported here uses an interference paradigm to answer the questions above pertaining to the cognitive (and potentially neural) sources of developmental change in memory. A secondary goal was to use developmental evidence to differentiate between theoretical accounts of interference: consolidation (Dewar et al., 2007; Wixted, 2004), active inhibition (Anderson, 2003), and configural encoding (Humphreys et al., 1989; Yim et al., 2013). To this end, predictions derived from each account can be compared. First, if interference is driven exclusively by a disruption of consolidation (Wixted, 2004), PI and RI effects should not differ between items that are unique and those that are
repeated across learning phases (i.e., overlapping items), as this theory predicts that any effortful new learning should disrupt consolidation and as a result produce interference. Additionally, analysis of developmental differences in the magnitude of interference effects may produce insight into the mechanistic source of these effects. Specifically, if interference is a function of inhibition at retrieval (Anderson, 2003), adults should demonstrate weaker PI and stronger RI effects than children, since the ability to inhibit prepotent responses increases with age (Brocki & Bohlin, 2004), and the magnitudes of PI and RI should be negatively correlated. Conversely, stronger RI in children may suggest a role of encoding, as recent work has suggested that children are less likely to encode complex associative structures than are adults (Yim et al., 2013). In addition, the encoding account predicts that adults’ ability to incorporate context information into a configural code should reduce RI effects in this age group.
EXPERIMENT 1

In Experiment 1 we sought to gain insight into developmental change by comparing the magnitudes of PI and RI between preschoolers and adults. Previous literature suggests that the magnitude of RI may remain stable between the ages of 4 and 7 years (Howe, 1995; Lee & Bussey, 2001). However, these studies did not include an adult comparison group, so it is unclear whether the mechanisms responsible for this effect are fully developed by this age range. Unlike RI effects, some work suggests that PI effects decrease between childhood and adulthood (Kail, 2002; Yim et al., 2013).

We also investigated the mechanisms of interference in Experiment 1 by manipulating the amount of overlap between associated elements in a new experimental paradigm designed to measure effects of both PI and RI on associative learning. This design allowed us to compare interference effects between elements that were unique and those that overlapped across different phases of the task. Comparing the magnitudes of PI and RI between ages and stimulus types may provide insight into the mechanisms of interference, as well as how these mechanisms develop.

Method

Participants

Thirty-four preschool-aged children (m = 5.31 years, SD = 0.24 years, range = 4.8-5.8 years, 18 females) and 28 college undergraduates (9 females) participated in this experiment. Children were tested in local preschools located primarily in middle class
neighborhoods of a large Midwestern city. They were recruited on the basis of returned permission slips and received stickers for participating. Adults were recruited from introductory psychology classes and received partial course credit.

**Stimuli**

Experimental stimuli consisted of illustrations of three familiar objects from each of four categories—animals (e.g. turtle), vehicles (e.g. boat), clothing (e.g. baseball cap), and furniture (e.g. lamp)—for a total of 12 objects. Objects were presented to participants in pairs selected arbitrarily from different categories. Additional stimuli included a visual occluder and two characters familiar to children—Winnie the Pooh (referred to as Pooh Bear) and Mickey Mouse (see Figure 1).

Across three experimental phases participants learned to associate pairs of objects with one of the two characters. Phase 1 and Phase 3 contained the same set of contingencies, whereas a different set was learned in Phase 2. Each set of stimuli contained two types of pairs: overlapping and unique. Overlapping pairs consisted of the same objects presented in different combinations and associated with different characters across sets. For example, using abstract notation for objects (A, B, C, and D) and characters (X and Y), if the overlapping pairs in Phase 1 were AB → X and CD → X, in Phase 2 the new pairings might be AC → Y and BD → Y. Note that in Phase 2 overlapping pairs were novel combination of previously presented elements. Conversely, unique pairs consisted of different elements across sets. Each set contained four pairs in total: two overlapping and two unique.
Figure 1. Experiment 1 trial sequence: on each trial participants saw a pair of objects that was stationary until response, then rose into the visual occluder and reappeared by the associated character.

On each trial participants were presented with a pair of objects, along with a visual occluder and two characters (see Figure 1). The spatial locations of characters remained constant throughout the experiment. In contrast, the colors of the background and the occluder provided contextual cues that remained constant within the phase, but varied across the phases. Specifically, pairs were presented either on a light gray background with a black occluder or on a dark gray background with a white occluder. These contexts were assigned to phases, with the assignment counterbalanced across participants.

Procedure

Children were tested in a quiet room in their preschools and adults were tested in the lab on campus. The task was presented to children on a touchscreen monitor and to adults on a standard computer monitor. The main experiment consisted of three experimental
phases, in which participants learned to associate pairs of objects with different characters. In Phases 1 and 3, the same set of contingencies was learned in a single context, whereas in Phase 2 a different set was learned in a different context. Between each phase participants were given a one-minute break, in which adults were asked to sit quietly and children received a sticker. Each phase included five blocks of eight trials, for a total of 120 trials across the experiment. Each pair of objects was seen twice per block, with trial order randomized for each block and each participant. Additionally, the spatial position of objects in each pair (top or bottom) was counterbalanced within each block. The entire experiment took approximately 25 minutes for children and 20 minutes for adults.

Prior to the experiment, participants were shown a pair of objects and told that these objects would disappear into this tunnel [experimenter pointed to the occluder] and pop out by one character, either Pooh Bear or Mickey Mouse [experimenter pointed to the characters]. The participants’ task was to predict where the objects would reappear. Child participants responded on each trial by touching the appropriate character on the touchscreen, while adults responded by pressing the left or right arrow keys corresponding to their choice. After a response was made, the bottom object in the pair moved upward and collided with the top object, before both items moved into the occluder and reappeared approximately 2s later by the appropriate character (see Figure 1). At the end of the trial, participants received explicit feedback about the accuracy of their prediction: they heard a high tone following correct responses or a low tone following incorrect responses. Children also received additional verbal feedback by the
experimenter, e.g. “Great job, those do go to Pooh Bear” or “Uh oh, those actually go to Mickey Mouse.”

The main experimental task was preceded by a warm-up phase, in which participants received instructions using age-appropriate language and the opportunity to become familiar with the task through practice trials. Stimuli for these practice trials consisted of four simple shapes and colors (e.g. blue circle) combined into two pairs. One pair was associated with Pooh Bear and one with Mickey. These pairs were presented with a blue occluder on a white background. Warm-up trials were presented in random order until participants correctly predicted the outcome on five consecutive trials. All participants completed the warm-up phase and proceeded to the experiment proper.

Results and Discussion

Six children were not included in analyses due to failure to complete the task (n = 2), failure to follow task instructions (n = 1), or computer failure (n = 3). Additionally, because the purpose of the experiment was to understand interference of learned information, we excluded participants who failed to exceed 70% accuracy in the first phase for either overlapping or unique pair types. Three additional children and four adults were excluded as a result of this criterion. The final sample included 25 preschoolers (m = 5.31 years, SD = 0.26 years, range = 4.8-5.8 years, 12 females) and 24 adults (8 females).

Children and adults learned quickly in the warm up phase of the experiment: the average number of trials required to reach the criterion of five consecutive correct trials was 5.21 for children (SD=0.51, min=5, max=7), and 5.5 for adults (SD=1.25, min=5, max=9).
To measure PI and RI effects we compare accuracies in the first and subsequent phases. Accuracy in Phase 1 is considered baseline as it measures initial learning. Learning in Phase 2, in contrast, may be influenced by what was already learned in Phase 1. Similarly, information learned in Phase 2 may affect memory for what was learned in Phase 1, leading to changes in accuracy in Phase 3. The analysis, however, is not straightforward, as simply comparing accuracies across phases leads to ambiguity regarding the cause of any differences. For example, attenuation of accuracy could be due to simple memory decay or other task effects, with interference playing no significant role.

We approach this problem by comparing accuracies for each pair type (i.e., overlapping and unique) averaged within specific blocks. Specifically, PI can be estimated by comparing accuracy of overlapping and unique pairs in the first block of Phase 1 and Phase 2. PI is inferred from attenuated learning of overlapping (but not unique) pairs in the beginning of Phase 2 compared to the beginning of Phase 1. RI can be estimated by comparing accuracy of overlapping and unique pairs in the last block of Phase 1 and the first block of Phase 3. RI is inferred from attenuated learning of overlapping (but not unique) pairs in the beginning of Phase 3 compared to the end of Phase 1. Finally, savings can be estimated by comparing accuracy in block 1 of Phase 1 and block 1 of Phase 3 for overlapping and unique pairs. Therefore, a significant interaction between phase and pair type provides unambiguous evidence of interference, as a pair type comparison controls for memory decay and task effects, and addresses whether any new learning potentially causes interference as predicted by the consolidation account (Wixted, 2004).
Figure 2. Accuracy results for all blocks and phases in Experiment 1, for children (top row) and adults (bottom row). Results are separated by pair type (unique and overlapping). Error bars indicate standard error of the mean.

Figure 2 shows children’s and adults’ average accuracy across all blocks in each phase, separated by pair type. Including all blocks in the analysis, however, would be highly conservative, as the comparison would assume effects of interference to last across the entire phase. As a result, we measure PI effects by comparing accuracies in the first block only of Phases 1 and 2 (see Figure 3). As discussed above, an interaction between phase and pair type provides unambiguous evidence of interference unaffected by fatigue or other task effects.

To analyze PI we performed a 3-way mixed ANOVA with Phase (Phase 1 vs. Phase 2) and pair type (Overlapping vs. Unique) as within-subject factors and age (Children vs. Adults) as a between-subject factor. There was a significant phase by pair type
interaction, $F(1,47) = 9.29$, $p = .004$, $\eta_p^2 = 0.17$, but no three-way interaction, $p = .26$, thus suggesting that the magnitude of PI may not differ between children and adults. Planned comparisons indicated that attenuation of accuracy was marginally significant in children for overlapping pairs, $t(24) = 1.90$, $p = .07$, Cohen’s $d = 0.38$, but not for unique pairs, $p = .48$. Similar effects were found in adults: attenuation was significant for overlapping pairs, $t(23) = -4.29$, $p < .001$, $d = 0.88$, but not for unique pairs, $p = .23$. Children and adults, then, experienced comparable magnitudes of PI when beginning to learn overlapping pairs in Phase 2.

*Figure 3.* Accuracy results for analyzed blocks in Experiment 1, for children (top row) and adults (bottom row). Results are separated by pair type (unique and overlapping).
We measured RI effects by comparing accuracy during the last block of Phase 1 and the first block of Phase 3 (see Figure 3). The logic of this comparison is that in the absence of RI or memory decay there should be no difference in accuracy between these blocks, as the pairs presented in each were identical. A three way mixed ANOVA with Phase (Phase 1 vs. Phase 3) and pair type (Overlapping vs. Unique) as within-subject factors and age (Children vs. Adults) as a between-subject factor revealed a significant three-way interaction, $F(1,47) = 18.56, p < .001, \eta^2_p = .28$, indicating that the magnitude of RI varied across age groups.

To better understand this interaction we performed separate Phase by Pair type repeated-measures ANOVAs for children and adults. The interaction between Phase and Pair type was significant in children, $F(1,24)=32.87, p<.001, \eta^2_p = .58$, but not in adults, $p = .62$. Planned comparisons suggest that children’s accuracy was significantly attenuated for overlapping pairs, $t (25) = -7.49, p < .001, d = 1.79$, but not for unique pairs, $p = 1$. In adults accuracy attenuated somewhat for both overlapping, $t (23) = -2.63, p = .015, d = 0.59$, and unique pairs, $t (23) = -3.19, p = .004, d = 0.99$. While children clearly exhibited strong RI, results in adults were somewhat ambiguous: it is not clear if RI affected both pair types, or if participants experienced simple memory decay for both pair types.

To gain more insight into the magnitude of RI effects, we calculated savings effects by comparing performance in the first block of Phase 1 and the corresponding block of Phase 3. We performed a three-way mixed ANOVA with Phase (Phase 1 vs. Phase 3) and Pair type (Overlapping vs. Unique) as within-subject factors and age (Children vs. Adults) as a between-subject factor, and found a significant three-way interaction, $F(1,47) = 7.27, p=.01, \eta^2_p=.13$, suggesting that the magnitude of savings effects varied as
a function of pair type and age. To examine these relationships more closely we performed separate Phase by Pair type repeated-measures ANOVAs in children and adults. A significant interaction was found between these factors in children, \( F(1,24) = 12.71, p = .002, \eta^2_p = .35 \). Paired-samples t-tests revealed that accuracy for overlapping pairs was attenuated, \( t(24) = -2.06, p = .05, d = 0.41 \), while for unique pairs accuracy improved, \( t(24) = 2.70, p = .013, d = 0.54 \). Remarkably, these results suggest that children’s performance for overlapping pairs was actually worse in Block 1 of Phase 3 than in Block 1 of Phase 1. Therefore, re-learning the same information attenuated after learning in Phase 2.

In contrast, the Phase by Pair type ANOVA for adults revealed no significant interaction between these factors, \( p=1 \), although a main effect of Phase was found, \( F(1,23) = 8.90, p = .007, \eta^2_p = .28 \), indicating that for both pair types adults were more accurate in Phase 3 than in Phase 1. These findings indicate significant savings in adults as accuracy in Block 1 improved from Phase 1 to Phase 3.

In sum, these results suggest that children were prone to marked RI for overlapping, but not unique pairs. This interference was bordering catastrophic as their accuracy for overlapping pairs dropped to worse than when learning the same pairs for the first time in Phase 1. In contrast, adults exhibited little evidence of RI.

We also computed the correlations between RI and PI effects in children and adults to gain some insight into whether the mechanistic bases of these effects are unitary or dissociable. Specifically, if the same mechanism causes both PI and RI we would expect the magnitudes of these effects to be correlated. To calculate PI effects we measured the change in accuracy between the first block of Phases 1 and 2 for overlapping and unique
pairs, and calculated the difference of these changes for each participant. Similarly, to measure RI we took the difference of the change in accuracy between the last block of Phase 1 and the first of Phase 3 for each pair type. These correlations between the magnitudes of PI and RI were negligible in children, $r(24) = .15, p = .48$, and adults, $r(23) = -.21, p = .32$, suggesting that different mechanisms may be responsible for PI and RI effects.

Overall, results of Experiment 1 indicate that (a) attenuation transpired primarily for overlapping pairs, (b) severe RI effects transpired in children, but not in adults, (c) comparable PI effects were found in children and adults, and (d) the magnitudes of PI and RI were not correlated in either children or adults.

The finding that performance attenuated only for overlapping pairs in most cases suggests that disruption of consolidation is unlikely to be the only source of interference. If dynamics of consolidation alone were responsible for interference (Dewar et al., 2007; Wixted, 2004), attenuation should have been equal for both pair types, as pairs were randomly intermixed within each block.

Additionally, the developmental pattern of the magnitude of interference effects is inconsistent with the idea that forgetting stems from frontal lobe-mediated inhibition of distracting contingencies (Anderson, 2003; Anderson & Spellman, 1995). In particular, if interference was mediated by active inhibition we would expect adults to demonstrate more RI and less PI than children, as a result of efficient inhibition of overlapping contingencies from Phase 1. Finally, the lack of correlation between PI and RI suggests that different mechanisms may be contributing to these effects, which is also inconsistent with predictions of the inhibition account.
Although this experiment has not supported the ideas that interference is caused solely by consolidation processes or active inhibition, it is not clear from these results what the mechanism(s) are. One possibility is that the locus of interference lies in encoding processes. Specifically, the complexity of participants’ associative structures may determine how vulnerable these structures are to interference. For example, it was possible in this experiment to be successful in Phase 1 by simply encoding associations between single objects and the corresponding character (e.g. Turtle–Pooh Bear). In this case interference would be expected to occur in subsequent phases for overlapping pairs, because each single object was associated with the other character in Phase 2 (e.g. Turtle–Mickey). Of course, it would be possible to encode more complex associative structures, such as by including both objects or the context (i.e. the colors of the background and visual occluder). Previous work suggests that adults are more likely to bind context and item information (Sluzenski et al., 2006; Yim et al., 2013), so it seems possible that adults successfully encoded contextual features of the background that co-varied with the set of pairs presented in a particular phase, and that this configural encoding protected information from RI.

To examine this possibility, we conducted Experiment 2. In Experiment 2, we eliminated the differences in visual context, such that the context was identical in all three phases. If participants spontaneously encoded the visual context in any phase during Experiment 1, interference should increase in Experiment 2.
EXPERIMENT 2

Method

Participants

A total of 37 preschool-aged children participated in this experiment, with a mean age of 5.29 years (SD = 0.23, min = 4.93, max = 5.69, 15 females). As in Experiment 1, children were recruited from local day cares and preschools, and received stickers for their participating. Thirty-five adults also participated (12 females), and received partial credit for an introductory psychology course as compensation.

Stimuli and Procedure

All stimuli were identical to those of Experiment 1, except that the visual context did not vary across phases or training trials. In all trials of the main experiment and the practice phase, the visual context consisted of a light grey background with a black visual occluder. The structure of contingencies between pairs of objects and characters across phases was the same as in Experiment 1, as was the task procedure.

Results and Discussion

Ten children were excluded from the analysis after not completing the task due to fatigue (n = 5), computer error (n = 3), or terminating the task for lunch or being picked up by a parent (n = 2). An additional child was excluded due to an undisclosed diagnosis of autism spectrum disorder. As in Experiment 1, we also excluded participants whose mean accuracy during Blocks 2-5 of Phase 1 was below 70% for either overlapping or
unique pairs. We excluded an additional three children and two adults as a result of this criterion. The final sample, then, consisted of 23 children with a mean age of 5.38 years (SD=0.22, min=5.04, max=5.69, 9 females), and 33 adults (12 females). Children reached the criterion of five consecutive practice trials after a mean of 5.26 trials (SD = 0.53, min = 5, max = 7), and adults after a mean 5.91 trials (SD = 2.75, min = 5, max = 17).

![Figure 4](image)

*Figure 4.* Results of Experiment 2: accuracy for children (top row) and adults (bottom row) for all blocks and phases.

Figure 4 shows children’s and adults’ accuracy for overlapping and unique pairs in each block and phase. As in Experiment 1, we calculated PI by comparing accuracy for each pair type in the first block of Phases 1 and 2 (see Figure 5). A mixed three-way ANOVA with Phase (Phase 1 vs. Phase 2) and Pair type (Overlapping vs. Unique) as within-subject factors and age (Children vs. Adults) as a between-subject factor indicated no significant three-way interaction, $p = .43$, suggesting that attenuation in Phase 2 did
not vary between children and adults, as in Experiment 1. The two-way interaction between block and pair type, however, did reach significance, $F(1,54) = 12.02$, $p = .001$, $\eta_p^2 = .18$, suggesting that PI was a factor in these age groups. Planned comparisons revealed that attenuation of children’s accuracy was significant for overlapping pairs, $t(22) = 3.60$, $p = .002$, $d = 0.75$, but not for unique pairs, $p = .65$. In adults, accuracy for overlapping pairs was non-significantly attenuated, $p = .85$, while accuracy for unique pairs was significantly benefitted, $t(32) = 2.97$, $p = .006$, $d = 0.45$.

**Figure 5.** Results of Experiment 2: accuracy for children (top row) and adults (bottom row) for specific blocks used to measure PI, RI, and savings effects.
RI was measured by comparing accuracies in the last block of Phase 1 to the first block of Phase 3. A three-way mixed ANOVA with Phase (Phase 1 vs. Phase 3) and Pair type (Overlapping vs. Unique) as within-subject factors and age (Children vs. Adults) as a between-subject factor indicated a marginally significant three-way interaction, $F(1,54) = 3.91, p = .053, \eta_p^2 = .068$. To examine the possible relationship between age and the magnitude of RI we next completed separate Phase by Pair type ANOVAs for children and adults. The interaction between these factors was significant in children, $F(1,22) = 18.68, p < .001, \eta_p^2 = .46$, as well as adults, $F(1,32) = 7.73, p = .009, \eta_p^2 = .20$. Note that this in contrast to Experiment 1, in which the interaction was only significant in children. Attenuation of accuracy in children was significant for overlapping pairs, $t(22) = -6.42, p < .001, d = 1.78$, but not unique pairs, $p = .21$. For adults, there was substantial attenuation for overlapping pairs, $t(32) = -4.77, p < .001, d = 0.86$, as well as some attenuation for unique pairs, $t(32) = -2.26, p = .033, d = 0.40$.

As in Experiment 1, we also calculated savings effects (i.e. the benefit to performance in the beginning of Phase 3 as a result of having already learned the same information in Phase 1), by comparing performance in the first block of Phases 1 and 3. A three-way mixed ANOVA with Phase (Phase 1 vs. Phase 3) and Pair type (Overlapping vs. Unique) as within-subject factors and age (Children vs. Adults) as a between-subject factor revealed a significant three-way interaction, $F(1,54) = 6.22, p = .016, \eta_p^2 = .10$, suggesting that savings depended on both the pair type and age group. To more clearly understand this relationship we performed separate repeated-measures ANOVAs with phase and pair type as factors for children and adults. The interaction was significant in children, $F(1,22) = 20.63, p < .001, \eta_p^2 = .48$, and in adults, $F(1,32) = 5.64, p = .024$,
Planned comparisons revealed that children’s accuracy was significantly higher in the beginning of Phase 3 for unique pairs, $t(22) = 4.59, p < .001, d = 0.961$, and significantly lower for overlapping pairs, $t(1,22) = -2.13, p = .045, d = 0.66$. Conversely, in adults accuracy was significantly higher in the beginning of Phase 3 for both unique, $t(32) = 6.40, p < .001, d = 1.15$, and overlapping pairs, $t(32) = 2.96, p = .006, d = 0.51$.

As in Experiment 1, then, RI affected children’s performance to the extent that performance was actually worse for overlapping pairs when re-learning information that had been introduced in Phase 1, whereas performance for unique pairs was benefited. In contrast, adults experienced savings effects for both pair types, suggesting that RI effects were not catastrophic in this age group.

Additionally, we again measured the correlations between the magnitudes of PI and RI, and as in Experiment 1 found no correlation in children, $r(22) = .038, p = .86$, or adults, $r(32) = .17, p = .34$.

The goal of Experiment 2 was to determine whether adults may have configurally encoded visual contextual information to reduce RI in Experiment 1. To investigate this we compared accuracies in the beginning of Phase 3 and the end of Phase 1 with mixed three-way ANOVAs with Phase (Phase 1 vs. Phase 3) and pair type (Overlapping vs. Unique) as within-subject factors and experiment (Experiment 1 vs. Experiment 2) as a between-subject factor for children and adults. The three-way interaction between block, pair type, and experiment was significant when comparing adults’ RI effects, $F(1,55) = 4.42, p = .04, \eta^2_p = .074$, suggesting that the magnitude of adults’ RI effects was significantly greater when visual contextual cues were not provided in Experiment 2. No other three-way interaction reached significance when comparing PI and RI effects across
Experiments 1 and 2 in children or adults. This result suggests that adults may have avoided RI effects in Experiment 1 by encoding covarying contextual information. If this is the case, then training adults to encode information configurally may attenuate interference effects. To examine this possibility, we conducted Experiment 3.
EXPERIMENT 3

In Experiments 1 and 2 we introduced a new experimental paradigm designed to measure interference effects in children and adults. It was found that PI and RI were present only for overlapping sets of information, and that children were much more susceptible to RI than were adults. Comparisons of adult performance in Experiments 1-2 suggested that adults may have been less susceptible to RI due to configural encoding of visual contextual information. In this experiment we use a training study to more directly assess the effect of configural encoding on adults’ susceptibility to RI. Although it would be optimal to perform the experiment with both children and adults, introduction of the described below training substantially increased the length of the experiment, thus making it impractical to conduct this experiment with children.

The task implemented in Experiment 3 is very similar to those in the first two experiments, but contains several key changes, which were made to encourage configural encoding. First, adults began the task by learning words corresponding to pairs of objects. This training phase of the task was designed to strongly encourage adults to attend to both objects in each pair, as well as the word, so that each pair of objects would become part of a complex associative structure. Crucially, adults only learned words corresponding to pairs of objects that would later be learned in Phase 1 (and re-learned in Phase 3). This design allowed us to determine the effects of learning words corresponding to unique and overlapping pairs that were later associated with characters.
in the main experimental task. The main experimental task was very similar to that of Experiments 1 and 2, with some minor modifications designed to further encourage adults to consider each pair of objects as a single associative unit. We hypothesized that adults who were more successful at configural encoding of overlapping pairs in the training phase would be less susceptible to RI in the main experimental task.

Method

Participants

Sixty-eight adults (37 females) participated in this experiment, and received partial course credit for their participation.

Stimuli

Twelve illustrated objects were presented to participants in pairs identical to those used in the first two experiments. These pairs were divided into the same two sets seen in Experiments 1 and 2 and were again associated with familiar characters (Pooh Bear and Mickey Mouse) across three main experimental phases. As in Experiment 2, stimuli were seen on a light gray background throughout the entire experiment.

A central goal of this experiment was to encourage participants to encode the stimuli configurally, discouraging associations of a single object with a character in the main task. To this end, we made minor changes to the task stimuli. First, pairs of objects were enclosed in a dark gray border (see Figure 6). Additionally, each panel (containing both objects) was referred to participants as a single object, and the spatial location of each object in the panel was consistent throughout the experiment. Finally, no visual occluder was presented and objects did not move around the screen, unlike in Experiments 1 and
These changes were made so that objects would not be perceived as separate entities that could move independently.

Figure 6. Sample stimulus configuration during a single trial of the training phase of Experiment 3.

Procedure

This experiment included a training phase, as well as three main experimental phases (referred to as Phase 1, Phase 2, and Phase 3) that were very similar to the main task in Experiments 1 and 2. Instructions were given prior to the training phase, as well as the first experimental phase. As the number of trials needed to reach criterion during the practice phase of Experiments 1 and 2 was generally very low, no warm-up trials were included in this experiment.

During the training phase, participants learned to associate words with the four pairs of objects that would later be associated with characters in Phases 1 and 3. Each pair of objects was presented as a single panel and associated with a label. For example, the panel containing a turtle and t-shirt was associated with the label "dax." On each training
trial, participants were presented with a word near the center of the screen, as well as four object panels placed near the bottom of the screen (see Figure 6). The spatial location of each panel was counter-balanced and presented in random order across the training phase.

The four choices of panels were constructed to encourage participants to configurally encode both objects within the panel. As shown in Figure 6, on each training trial one panel was the correct choice, one panel was a foil that would be correct for a different word, and the remaining two panels were combinations of the target and foil panels. In this way, there were four different objects presented in different combinations across the four panels, and no single object could predict the correct answer choice. As such, a single two-way association between the word and a single object would be insufficient to identify the correct panel. Additionally, participants could not simply find one "correct" choice (i.e. recognize one panel that was the correct choice in a previous trial), as the foil panel was the correct choice for a different word label. As such, a single two-way association between the two objects in any given panel would also be insufficient for a correct response. Below each panel was a number (1-4). Participants were instructed to choose which of the four object panels was denoted by the given word by pressing the 1, 2, 3, or 4 button on the keyboard. Auditory feedback was given in the form of a high tone for correct responses or a low tone for incorrect responses. The length of this phase depended on participants’ performance. Participants completed a minimum of 40 trials, and continued in the task until they responded with 90% or higher accuracy within a moving window of 40 trials, or until completion of a maximum of 120 trials. Participants then proceeded to the experiment proper that started with Phase 1.
During Phase 1 of the main experimental task, participants were shown one panel of objects, along with four words, and were asked to indicate which word denoted the given panel by pressing the number 1, 2, 3, or 4 on the keyboard (see Figure 7). Auditory feedback was again given, with high tones accompanying correct responses, and low tones incorrect responses. The purpose of this part of each trial was again to influence participants to consider the panel of objects as one configural whole when encoding the association between the panel and the appropriate character. After participants chose which word denoted the given object, all text disappeared and participants were asked to indicate whether each panel belonged to Pooh Bear or Mickey by pressing the left or right arrow key. Following this choice, the panel of objects disappeared and reappeared by the correct character (regardless of the participant’s choice). Note that the pair of objects did not slide into and out of a visual occluder as in the first two experiments.
Auditory feedback was again given for correct and incorrect responses as indicated above.

In contrast to Phase 1, Phases 2 and 3 did not include the word learning component, but simply required participants to indicate whether panels belonged to Pooh Bear or Mickey. Other than the changes noted above, these phases did not differ from those in the first two experiments: Phase 2 included two unique pairs of objects not seen in the first phase (or in the training phase) and two overlapping pairs which were recombinations of objects seen in the previous phases. Phase 3 was again identical to the first phase, except that no word learning component was included.

Results and Discussion

One participant was excluded from the analysis due to computer failure. Additionally, 14 participants were excluded due to low accuracy for either overlapping or unique pairs, according to a criterion of at least 70% for both pair types in Blocks 2-5 of Phase 1, as in Experiments 1 and 2. Finally, we excluded an additional 13 participants for failing to reach criterion during the word-learning phase (i.e. reaching the maximum of 120 trials without exhibiting evidence of learning). These participants were excluded because it is unclear why they failed to reach criterion and whether this failure was due to the inability to configurally encode or some other factor (e.g. confusion at the task or slow learning). Following this exclusion the final sample consisted of 40 adults (22 females).

Table 1 summarizes performance in the training phase, in which adults learned to match a given word with the correct pair of objects. Recall that during each trial of Phase 1, participants performed a similar task in which they matched a given pair of objects with the correct word. Average accuracy during this word-learning portion of Phase 1
was 92.4% (SD = 13%) for overlapping pairs and 92.4% (SD = 10%) for unique pairs. This indicates that participants were able to successfully retrieve the mapping between the pair of objects and the associated word during Phase 1.

<table>
<thead>
<tr>
<th>Training Phase Summary</th>
<th>Mean</th>
<th>Median</th>
<th>S.D.</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of trials to criterion</td>
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<td>80</td>
<td>20.57</td>
<td>40</td>
<td>117</td>
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<tr>
<td>Percent accuracy for overlapping pairs</td>
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<td>67.03</td>
<td>12.52</td>
<td>40.00</td>
<td>92.59</td>
</tr>
<tr>
<td>Percent accuracy for unique pairs</td>
<td>70.59</td>
<td>71.46</td>
<td>12.59</td>
<td>40.82</td>
<td>92.86</td>
</tr>
</tbody>
</table>

*Table 1.* Summary statistics for performance in the training phase of Experiment 3.

The purpose of this experiment was to determine whether configural encoding of overlapping elements would lead to a reduction of interference effects. To this end, we first analyze overall interference effects in the main experimental task (i.e. associating pairs of objects with characters) as in the first two experiments. Because we instantiated a number of changes to the task structure, we do not directly compare interference effects to those of prior experiments. Rather, we examine whether variability in word learning explains variability in RI effects.
Figure 8. Accuracy for each block and phase of the main task in Experiment 3.

Figure 8 shows the proportion of accuracy in each block and phase of the main experimental task. As in Experiments 1 and 2, PI was calculated by comparing accuracies in the first block of Phases 1 and 2 for each pair type (see Figure 9). A repeated-measures ANOVA revealed a significant interaction between these factors, $F(1,39) = 8.01, p = .007, \eta_p^2 = .17$. Accuracy for overlapping pairs was not significantly different between these blocks, $p = .90$, while accuracy for unique pairs was significantly higher in the beginning of Phase 2, $t(39) = 3.50, p = .001, d = 0.56$. This suggests that similar to Experiments 1 and 2, participants as a group exhibited PI.

We also measured RI by comparing accuracies in the last block of Phase 1 and the first block of Phase 3 for both pair types. The interaction between these factors was also significant, $F(1,39) = 25.76, p < .001, \eta_p^2 = .40$, suggesting that adults were subject to RI, as there was greater attenuation for overlapping pairs, paired-sample $t(39) = -6.86, p < .001$ than for non-overlapping pairs, $p = .50$.

We also conducted an ANOVA comparing the first blocks of Phases 1 and 3 to measure savings effects. There was again a significant interaction in this comparison, $F(1,39) = 14.43, p < .001, \eta_p^2 = .27$. Paired-samples $t$-tests revealed that accuracy for overlapping pairs did not differ between the first block of Phases 1 and 3, $p = .45$, while
accuracy improved for unique pairs, $t(39) = 6.41, p < .001, d = 1.05$. As in the first two experiments, the magnitudes of PI and RI were not correlated, $r(39) = .053, p = .75$. Taken together, these results indicate that adults overall demonstrated robust PI and RI effects. We next analyze effects of training on interference.

![Figure 9](image.png)

*Figure 9.* Results for specific blocks related to PI, RI, and savings effects in Experiment 3.

The primary purpose of this experiment was to determine whether training adults to more configurally encode associative structures would reduce interference effects. We address this question with a series of simple linear regression analyses to determine the effect of accuracy for overlapping and unique pairs during training on the magnitudes of PI and RI. If configural encoding modulates the magnitude of RI in adults, then the ability to map configural associations between objects and words during the training phase of the task should predict the magnitude of RI during the experimental task.

To assess the relationship between an individual’s ability to configurally encode information and the magnitude of interference we performed a linear regression and found that individuals’ accuracy for overlapping word mappings during training did not
predict susceptibility to PI, \( p > .2 \), but did predict their susceptibility to RI, \( \beta = -0.86, t(38) = -2.66, p = .011 \), and accounted for a reasonable amount of variance in RI, adj. \( R^2 = .14, F(1,38) = 7.06, p = .011 \). One possibility, however, is that better learners were just better, more engaged participants overall. If this is the case, then the same effects should transpire for unique pairs. However, accuracy for unique word mappings during training did not predict the magnitude of RI, \( p = .90 \), suggesting that the effect of configural encoding is information-specific and does not stem from superior configural encoding in general.

![Figure 10](image.png)

**Figure 10.** The effect of training accuracy for overlapping and unique pairs on RI effects in the main task of Experiment 3. Higher values of RI indicate greater interference. Points are slightly jittered for ease of viewing.
To further investigate effects of training, we performed a median split of the sample based on accuracy for mapping novel words to overlapping pairs during the training phase. We refer to participants with accuracies below the median split as "low learners" and those above the split as "high learners." Average accuracy for low learners was 57.44% (SD = 7.81%), and average accuracy for high learners was 76.67% (SD = 8.13%). Interference effects of low and high learners are presented in Figure 11. To determine whether low and high learners differed in their susceptibility to interference we performed a series of three-way ANOVAS with learning level as a between-subject factor.

Figure 11. RI effects for participants with high accuracy and low accuracy for overlapping pairs during training in Experiment 3.
When investigating PI effects by comparing accuracies of high learners and low learners in the first block of Phase 1 and the first block of Phase 2, the three-way interaction between Phase, Pair type, and learning level was not significant, $p=.61$, suggesting that PI did not vary as a function of learning during the training phase.

In contrast to PI, for which no effects of training were found, there was a marginally significant three-way interaction when calculating RI by comparing the difference between the last block of Phase 1 and the first of Phase 3 in these groups, $F(1,38)=3.81$, $p=.058$, $\eta^2_p=.091$, suggesting that higher learners experienced less RI when learning in Phase 3. We also used a mixed ANOVA to investigate the effect of training accuracy on savings effects by comparing accuracies in the first block of Phase 1 and the first block of Phase 3. A marginally significant three-way interaction was found, $F(1,38)=3.00$, $p = .092$, $\eta^2_p = .073$. We also performed a median split based on accuracy for unique pairs during the training phase, and no significant three-way interaction was found for RI effects, $p=.89$, or savings, $p=.53$. Again, these results suggest that configural encoding of overlapping information affects susceptibility to RI and experience of savings effects.

In this experiment, we again replicated PI and RI effects in adults with a modified experimental design, and provided evidence that success at configural encoding is associated with reduced vulnerability to RI. Specifically, we trained adult participants to associate objects within a pair together, and with a specific word label, thus encoding a configural representation of each pair. Participants’ success at encoding overlapping pairs in this way was a significant predictor of the magnitude of RI later in the task, suggesting that this encoding acted as a buffer against this form of interference. Interestingly, it was not the case that better configural learning in general experienced less RI, as accuracy for
unique pairs during training did not predict later susceptibility to RI. No effects of training on PI were found, however, which further suggests that PI and RI may stem from different mechanisms. We return to this issue again in the general discussion section.
GENERAL DISCUSSION

The purpose of this study was to gain developmental and mechanistic insights into the effects of interference (both proactive and retroactive) on associative learning. The primary findings of these experiments were that (1) interference is influenced by the amount of associative overlap between sets of information, (2) the magnitudes of PI and RI are uncorrelated in both children and adults, (3) children are much more susceptible to RI from overlapping information than adults, and (4) configural encoding of overlapping information may reduce RI in adults. We discuss each of these findings and their implications in more detail below.

In almost all cases, attenuation of learning occurred only when associative elements overlapped (i.e. were recombined) across the phases. This attenuation for overlapping elements was in stark contrast to learning for unique elements, which was not attenuated, and in most cases was facilitated. This finding is consistent with a number of findings suggesting the impact of stimulus overlap and similarity on the extent of interference effects (Anderson & Neely, 1996; French, 1999; McGeoch & McDonald, 1931; Morra, Garcon, Lucas, & Donovick, 2013; Wickelgren, 1965; Wickens, Born, & Allen, 1963). This finding is also compatible with developmental work on the DCCS task suggesting that perseveration is dependent on the amount of overlap between specific stimulus features (Zelazo et al., 2003), such that children are able to sort items according to a new rule when stimuli of different colors and shapes are used on the post-test, whereas
perseveration is severe when children are asked to sort the same stimuli in different ways. The finding that the magnitude of interference is strongly influenced by stimulus overlap is inconsistent, however, with recent claims that interference (particularly RI) is caused solely by a disruption of the consolidation process, independent of stimulus overlap (Dewar et al., 2007; Wixted, 2004). We return to the possible contribution of consolidation processes later in this discussion.

Although stimulus overlap is clearly an important factor for susceptibility to both PI and RI effects, overlap is not sufficient to explain interference effects, in that the magnitudes of these effects were not correlated in any experiment in children or adults, suggesting that the mechanisms underlying PI and RI may be dissociable. We suggest that investigating developmental changes between these age groups may provide insight into the mechanistic bases of interference, as well as how interference may affect cognitive development.

*Children’s Catastrophic Interference*

One noteworthy finding of these experiments was the magnitude of RI effects in children. In Experiments 1 and 2, children’s accuracies for overlapping pairs in Phase 3 were significantly lower than in Phase 1. This is remarkable, considering that the same set of information was presented in both phases, suggesting that not only was children’s memory for this information attenuated as a result of learning in Phase 2, it was actually more difficult to learn the same information a second time.

What could cause such a remarkable decline in children’s performance? One possibility, consistent with the inhibition at retrieval account (Anderson et al., 1994; Anderson, 2003; Anderson & Neely, 1996), is that children inhibited the information
presented in Phase 1 in order to learn new pairings in Phase 2. According to this theory, inhibition of a prepotent memory trace occurs as a result of retrieving weaker but more contextually appropriate memories (Anderson, 2003). As a result, more successful retrieval of new responses should be associated with greater inhibition of old responses, such that the magnitudes of PI and RI should be negatively correlated. As mentioned above, however, this was not the case in the experiments presented here.

The inhibitory account is also not consistent with the developmental pattern of results found in the current study. Interestingly, there is some debate in the literature as to whether children are able to efficiently inhibit prepotent memories. Some work suggests that preschool-aged children may not be able to efficiently inhibit non-relevant memories (Aslan & Bäuml, 2010; Bjorklund & Harnishfeger, 1990; Harnishfeger & Bjorklund, 1994). However, other work suggests that memory inhibition can be explicitly cued or can act as a presumably implicit, automatic process. Young children may be unable to inhibit memories given explicit instructions (Harnishfeger & Pope, 1996; but see Knott, Howe, Wimmer, & Dewhurst, 2011), while some work suggests that children preschool-aged and older are able to implicitly inhibit memory as well as adults (Zellner & Bäuml, 2005). One recent study, however, used a retrieval-induced forgetting paradigm to test this more implicit form of inhibition and found that kindergarteners did not demonstrate forgetting in a condition testing recognition memory, which suggests that this age group was not able to efficiently inhibit memory during retrieval (Aslan & Bäuml, 2010). In our task we did not explicitly instruct participants to forget information learned in Phase 1, although it is possible that children may have inhibited this information automatically while learning in Phase 2. To our knowledge, however, there is no reason to predict that
children would be more efficient than adults at inhibiting memory. As a result, we suggest that inhibition is insufficient to account for the finding that children experienced much stronger RI effects than adults in this study.

Although we suspect that inhibitory processes did not cause the difference in magnitude between RI effects in children and adults, some insight may be gained by examining other learning systems that experience similar levels of RI. The magnitude of RI in children is reminiscent of the catastrophic interference effects observed in simple connectionist models (McCloskey & Cohen, 1989; Ratcliff, 1990). In these models, new learning quickly causes substantial forgetting of previous knowledge. McCloskey & Cohen (1989) found that memory for an initial learning set began declining immediately upon learning new information, and accuracy for previous learned information quickly reached approximately zero percent. Human adults generally demonstrate much more modest RI effects (French, 1999), as they did in this study. A possible explanation for this reduction in RI was proposed by McClelland et al. (1995), who suggested that the interaction of a fast-learning hippocampal system and a slow-learning cortical system could protect information from interference by gradually integrating memory into the neocortex (i.e. by consolidation). In this way, memory is not disrupted by new learning that is rapidly acquired via hippocampal processes.

One possible explanation for children’s catastrophic-like RI in this study is immaturity of the hippocampal-cortical network. Specifically, children may have difficulty consolidating in the presence of new, overlapping information. Unique information, however, may be processed separately in the hippocampus and thus not subject to disruption.
It is possible, then, that immature consolidation processes in the hippocampal-cortical network contributed to the severe RI effects observed in children. However, it is clear that disruption of consolidation was not the sole cause of interference in the current experiments, as in most cases attenuation of accuracy was greater for overlapping pairs of objects. It is possible, however, that disruption of consolidation did not play a substantial role in these results because we allowed very little time (approximately one minute) between phases. One way to approach to this issue in future work would be to introduce a longer delay between learning phases, allowing consolidation of intact memory traces. If immaturity of consolidation processes does play a role in producing RI, interference should decrease with an opportunity to consolidate information more fully. Interestingly, delays were present in previous work (Howe, 1995; Lee & Bussey, 2001) suggesting that the magnitude of RI effects does not differ in children between the ages of 4 and 7 years. Children in Howe’s (1995) study were tested for memory 24 hours after initial learning, and those in Lee and Bussey’s (2001) study were tested three weeks after initial learning. We suspect that these delays may have allowed for greater consolidation of information and as a result made it more difficult to find developmental differences. One possibility, then, is that the dramatic age effects found in the current study at least partly reflects developmental differences in the speed and efficacy of consolidation processes.

It is also possible that consolidation could play a role in modulating PI effects. Specifically, one reason why children demonstrated comparatively little PI effects may be that information learned in Phase 1 was not well established in long-term memory, thus minimizing PI effects. This idea is consistent with a theory of children’s perseveration in the DCCS task that latent (long-term) memory in cortical regions causes perseveration by
overcoming active (short-term) memory for new contingencies (Morton & Munakata, 2002). If this is the case, PI would be expected to increase with consolidation during delays between Phase 1 and the remaining phases, and RI would be expected to decrease.

*Configural encoding and RI*

The reported results suggest that inhibition and consolidation are unable to account for the pattern of results demonstrated in this study and they implicate encoding in modulating interference effects, especially RI. Recall that in Experiment 1, RI effects were highly robust in children but were ambiguous in adults. In Experiment 2 we reduced the contextual separation between phases and found that RI effects increased in adults, but not in children. Our hypothesis is that adults used the contextual information available in Experiment 1 to reduce interference by encoding a configural association between the visual context and object-outcome contingencies.

Our finding of increased RI in adults (but not in children) when contextual cues were removed (Experiment 2) could suggest that adults are more likely to encode configural associations in the presence of additional cues. Indeed, some work suggests that configural encoding exhibits substantial improvement between preschoolers and adults (Rudy et al., 1993; Yim et al., 2013). Additionally, adults and older children are more likely to bind item and context information (Sluzenski et al., 2006). One possibility, then, is that adults, but not children, were able to take advantage of the contextual information available in Experiment 1.

Additional evidence for the possible role of configural encoding was found in Experiment 3, in which more successful configural encoding of overlapping items was predictive of smaller magnitudes of RI in adults. Crucially, successful encoding of unique
items did not predict the extent of RI. This suggests an important distinction: it is not that individuals who are generally better able to configurally encode information are less subject to interference, but that better encoding of information helps to protect that specific information from later forgetting.

Why would configural encoding reduce RI effects? One possibility is that it affects the similarity between sets of information (Humphreys et al., 1989). In our study, interference was found only for overlapping sets of information, and simple associations between overlapping elements could result in very similar associative structures between competing representations. For example, it was possible to succeed in Phase 1 by associating a single object with the corresponding character (e.g. Turtle–Pooh Bear). In Phase 2, however, each individual object in overlapping pairs was now associated with the other character (e.g. Turtle–Mickey). These two associations are highly similar in that there is only a single object, which is shared by both. However, integrating context information in these configurations (e.g., Turtle-White Occluder-Mickey) would substantially reduce this overlap, resulting in reduced RI.

Potential mechanisms of PI

If RI is modulated at least in part by configural encoding processes, what mechanisms influence PI effects? Previous work has suggested that PI effects are likely modulated neurally by activity in the frontal cortex (Shimamura et al., 1995), and some have argued that the cognitive underpinnings of PI may lie in executive control (Anderson, 2003) or cognitive flexibility (Morton & Munakata, 2002). It is clear from previous work that children’s prefrontal cortex (Nelson, Thomas, & de Haan, 2007) and cognitive control (Davidson, Amso, Cruess Anderson, & Diamond, 2006) are immature compared to those
of adults. One hypothesis, then, is that PI should be greater in children than in adults. Some work indeed supports this hypothesis (Kail, 2002). One noteworthy aspect of our results, then, is that PI effects were not greater in children than in adults.

One possible explanation of these results is that learning in Phase 2 did not challenge cognitive control sufficiently to demonstrate developmental differences. Only two new overlapping (and two unique) pairs were learned in Phase 2, and perhaps if more pairs had been presented developmental differences would have been more clearly delineated. Another possibility is that developmental differences were present, but that our measures were not sufficiently sensitive to detect them. Additionally, our measure of PI may have made it difficult to observe differences. Specifically, we would not expect accuracy in the beginning of Phases 1 or 2 to be below chance (50%), and so we would expect the differences between these to be modest.

Because we did not find developmental differences in the magnitude of PI, we make no claims as to the mechanistic basis of these effects. However, it is interesting to note that these effects were likely not modulated by configural encoding in this experiment. If PI and RI were both a function of differences in encoding, a positive correlation would be expected between PI and RI effects, in that more configural encoding should have reduced both PI and RI. In all experiments, however, PI and RI effects were uncorrelated, suggesting that the mechanistic bases of these effects may differ. Additionally, training adults to encode information more configurally did not affect the magnitude of PI in Experiment 3, again suggesting that configural encoding may not have played a significant role in modulating these effects in this experiment.
Interestingly, however, previous work has suggested that configural encoding may affect PI in some contexts. Specifically, Yim et al. (2013) produced a multinomial processing tree model which suggested that adults were better able to encode complex associative structures and were less prone to PI than were children, who were less likely to encode complex binding structures. Additionally, Humphreys et al. (1989) produced a model that was less susceptible to PI effects when encoding more complex configural associations. We suspect, then, that configural encoding and cognitive flexibility may both modulate PI effects, depending on the context of the task. Interestingly, some work suggests that the ability to bind associative elements together into a complex structure may neurally depend on prefrontal cortices (Newcombe, Lloyd, & Ratliff, 2007), again suggesting a link between PI, cognitive flexibility, and configural encoding. Regardless, more work is needed to differentiate the cognitive mechanisms of PI in children and adults.

Implications for early learning

The current work has a number of implications for our understanding of cognitive development. To begin, it suggests that interference can greatly affect children’s learning of overlapping sets of information. Language is one example of a set of highly structured and overlapping associative structures. The possibility of interference affecting language learning, then, seems quite high (see Levy, McVeigh, Marful, & Anderson, 2007, for a discussion on interference effects in second-language learning, for example). One hypothesis is that children who successfully form configural associative structures might be better able to learn language. Although to our knowledge this hypothesis has not been directly tested, Hills and colleagues have demonstrated an association between children’s
ability to learn language and the semantic structure of words in their vocabulary, such that children with highly dense, clustered semantic networks tend to learn language more quickly and have larger vocabulary size (Beckage, Smith, & Hills, 2011; Thomas T Hills et al., 2009; Thomas T. Hills, Maouene, Riordan, & Smith, 2010). This result suggests that children who are better able to encode interconnected (potentially configural) associative structures are better able to learn language.

In other tasks infants and young children seem to benefit from being exposed to multiple sources of correlated information, even when such information is redundant. For example, infants (Sloutsky & Robinson, 2013), as well as preschool-aged children (Sloutsky & Fisher, 2008), are able to learn to flexibly categorize the same stimuli differently in different contexts, but only when multiple sources of contextual differences are provided (e.g. background color, object size, and spatial location). Interestingly, when such rich contextual separation was provided, infant learning was not attenuated in a second phase (i.e. no PI effects were observed; Sloutsky & Robinson, 2013). This suggests that even children and infants may experience some benefit from configural encoding when multiple cues are provided.

This work has clear implications for the nature of learning and memory. Some previous work suggests that providing correlated redundant information aids learning in infants, children, and adults (Lupyan, Rakison, & McClelland, 2007; Sloutsky & Robinson, 2013; Smith, Colunga, & Yoshida, 2010). The current study suggests that correlated information may support learning and memory by allowing for more configural associative structures. More work is clearly needed to substantiate this
possibility, but this hypothesis has definite implications for education, as well as our understanding of the general mechanisms of learning and memory.
References


