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Retrieval-Induced Forgetting of Arithmetic Facts

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Retrieval-induced forgetting (RIF) is a widely studied phenomenon of human memory, but RIF of arithmetic facts remains relatively unexplored. In 2 experiments, we investigated RIF of simple addition facts (2 + 3 = 5) from practice of their multiplication counterparts (2 × 3 = 6). In both experiments, robust RIF expressed in response times occurred only for high-strength small-number addition facts with sums ≤ 10, indicating that RIF from multiplication practice was interference dependent. RIF of addition-fact memory was produced by multiplication retrieval (2 × 3 = ?) but not multiplication study (2 × 3 = 6), supporting an inhibitory mechanism of RIF in arithmetic memory. Finally, RIF occurred with multiplication practiced in word format (three × four) and addition tested later in digit format (3 + 4), which provides evidence that digit and written-word formats for arithmetic accessed a common semantic retrieval network. The results support the view that addition and multiplication facts are stored in an interrelated semantic network and that RIF of competing addition facts is an intrinsic process of multiplication fact retrieval.

Keywords: retrieval-induced forgetting, arithmetic, inhibition, numeral format

Retrieval-induced forgetting (RIF) occurs when repeated practice of a memory item impairs retrieval of related, unpracticed items. In the standard retrieval-practice paradigm (see, e.g., Anderson, 2003), participants study a list of category-exemplar pairs (fruit–orange, fruit–apple, drink–rum, drink–scotch). In a subsequent practice phase, they perform repeated cued-stem retrievals for a subset of pairs from half of the categories (e.g., fruit–or__). Participants finally receive a cued recall test for all the category-exemplar pairs on the original study list. The critical finding is that recall performance on unpracticed items from practiced categories (fruit–a__) is reduced relative to items from unpracticed categories (drink–r__). RIF is a robust phenomenon observed in a wide variety of memory tasks (Anderson, 2005; Johnson & Anderson, 2004; Koutstaal, Schacter, Johnson, & Galluccio, 1999; Levy & Anderson, 2002; Phenix & Campbell, 2004; Shaw, Bjork, & Handal, 1995). It is most often studied using episodic recall (Anderson, 2003; Anderson & Spellman, 1995; Norman, Newman, & Detre, 2007) or recognition (Spitzer & Bäuml, 2007), but it is also observed in semantic memory retrieval (Johnson & Anderson, 2004; Levy, McVeigh, Marful, & Anderson, 2007). Thus, the interfering effects of retrieval practice on memory for related information appear to be a pervasive feature of human memory.

It is surprising that no current theory of basic arithmetic memory (e.g., 3 + 4 = ?) incorporates an explicit role for RIF, possibly because so little is known about the phenomenon in this context (but see Campbell & Phenix, 2009; Phenix & Campbell, 2004). The potential role of associative interference in arithmetic learning has been considered for many years. On the basis of error analyses, Norem and Knight (1930, p. 563) proposed that children's difficulty learning the multiplication facts owed mainly to a problem of "promiscuous connection forming" between digits and their myriad numerical associations. In the last 25 years, several investigators have also considered associative interference among related number facts a major source of learning and retrieval difficulty (see, e.g., Ashcraft, 1992; Campbell, 1995; Lemaire & Siegler, 1995; Siegler, 1988). The underlying processes, however, have not been considered in the light of recent RIF research and the retrieval-practice paradigm.

In theory, RIF provides a measure of retrieval-induced inhibition of competing memory representations (Anderson, 2003; Levy & Anderson, 2002). Thus, in principle, RIF is diagnostic both of the occurrence of retrieval and of sources of competition in long-term memory. These features may be exploited to address important issues in cognitive arithmetic. For example, a central issue in cognitive arithmetic research is distinguishing direct memory retrieval of an answer from use of procedures such as counting (e.g., Metcalfe & Campbell, 2011). We would expect retrieval but not procedures to generate RIF of related memory items; consequently, RIF is potentially diagnostic of arithmetic strategy choice. Similarly, because RIF specifically affects retrieval competitors, it is specifically diagnostic of competition. This feature could be exploited, for example, to investigate the linguistic specificity of arithmetic facts (see, e.g., Rusconi, Galfano, & Job, 2007). Bilinguals could practice select number facts in one language and then be tested for evidence of RIF of related arithmetic facts in their other language. The presence or absence of cross-language RIF may be diagnostic of bilingual representation of arithmetic facts. We similarly examined cross-format RIF in Experiment 2 here to investigate whether different surface forms of problems (e.g., 4 × 8 vs. four × eight) access a common semantic memory represen-

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tation. The latter issue has been an unresolved point of controversy for more than two decades (e.g., Campbell, 1994; Campbell & Alberts, 2009; McCloskey, Harley, & Sokol, 1991; McCloskey & Macaruso, 1995). We foresee many potential applications, and these few examples serve simply to illustrate the potential for RIF and the retrieval-practice paradigm to inform cognitive arithmetic research.

In the present experiments, we investigated conditions under which practice of a multiplication fact (e.g., $2 \times 5 = ?$) affects memory performance for its addition counterpart ($2 + 5 = ?$). One purpose was to establish a direct empirical link between RIF phenomena observed in the standard retrieval-practice paradigm (see, e.g., Levy & Anderson, 2002) and RIF in number-fact memory. The standard paradigm has used recall probability or recognition probability as the main dependent measure of RIF. In contrast, experimental studies of interference effects in arithmetic memory have measured only response time (RT) or accuracy (e.g., Campbell & Phenix, 2009; Phenix & Campbell, 2004) or have not included the standard control condition (i.e., unpracticed items) used in the retrieval-practice paradigm (e.g., Campbell & Timm, 2000). The current experiment measured simple addition performance ($2 + 5 = ?$) following practice of the multiplication counterparts ($2 \times 5 = ?$) and compared this with performance for addition problems whose multiplication counterparts were unpracticed. Apart from RT and accuracy measures, we also obtained participants' self-reports of direct memory retrieval versus usage of a procedural strategy (e.g., counting or transformation) for each addition problem. Numerous studies support the utility of self-reports as experimental measures of adults' strategies for simple arithmetic (e.g., Campbell & Alberts, 2009; Campbell & Austen, 2002; LeFevre, Sadesky, & Bisanz, 1996; Metcalfe & Campbell, 2011; Seyler, Kirk, & Ashcraft, 2003; but see Kirk & Ashcraft, 2001; Thevenot, Castel, Fanget, & Fayol, 2010). North American university students report relatively high percentages of nonretrieval strategies for simple addition, especially for numerically large simple addition problems (e.g., $7 + 9$, $8 + 6$, etc.), but they also report some procedure use for small problems with sums ≤ 10 (e.g., $2 + 3$, $5 + 4$; Campbell & Xue, 2001; LeFevre et al., 1996). Thus, an experimental manipulation that increases procedure use for a specific addition fact (i.e., promotes a shift from retrieval to a procedure such as counting) has effectively induced RIF of that memory item. Consequently, the strategy self-reports provided a measure of retrieval probability analogous to that used in the standard retrieval-practice paradigm.

Representational Locus of RIF of Arithmetic Facts

Campbell and Phenix (2009) also examined the effects of multiplication practice on addition-fact retrieval. They created practiced and unpracticed multiplication problem sets from two nonoverlapping operand sets (2, 5, 7, 8 or 3, 4, 6, 9). Participants practiced multiplication problems composed of pairs of operands from one set and then were tested on corresponding addition problems (MP additions) and on addition problems composed from the unpracticed operand set (MU additions). The MP-addition problems are analogous to unpracticed items from the practiced categories in the standard RIF retrieval-practice paradigm, whereas the MU-addition problems are analogous to unpracticed baseline items from unpracticed categories. Their results showed RT interference for MP-addition relative to MU-addition problems, but the source of this effect was ambiguous. Interference could reflect categorical RIF of addition facts associated with the practiced operand family (i.e., 2, 5, 7, 8 or 3, 4, 6, 9) or RIF of specific addition facts (e.g., RIF of $2 + 5 = 7$ from practicing $2 \times 5 = 10$). In the current experiments, MP and MU practice sets were created with matched operands; specifically, each of the digits 2 through 9 occurred in four problems in each set. Thus, MP problems included the full set of operands as category retrieval cues. If addition RIF in number-fact memory is only categorical, then we would expect no difference in performance between MP addition and MU addition after multiplication practice. In contrast, if interference occurs at the item level (e.g., practicing $2 \times 5 = 10$ specifically interferes with retrieval of $2 + 5 = 7$), then performance of MP addition should present a performance decrement relative to MU addition.

Interference-Dependent RIF of Arithmetic Facts

Testing the full range of problems from $2 + 2$ to $9 + 9$ also allowed us to pursue another prediction. Anderson (2003) proposed the principle of *interference dependence* for RIF: If a target memory is strong, or a competitor memory is weak, then target retrieval practice is expected to produce weak RIF. In contrast, if a competitor is strong, then it will attract inhibition and RIF (Anderson, 2003; see also Levy et al., 2007; Norman et al., 2007). Given this, we would expect more RIF for small addition problems (sum ≤ 10) than large problems (sum > 10) because the former are strong competitors to their multiplication counterparts, whereas the latter are not. That is, small problems (e.g., $2 + 3 = 5$, $2 \times 3 = 6$) usually have higher memory strength than larger problems (e.g., $7 + 9 = 16$, $7 \times 9 = 63$; Campbell & Xue, 2001; LeFevre et al., 1996; Zbrodoff & Logan, 2005). Consequently, large addition facts should not interfere with their multiplication counterparts, and there should be little RIF produced by practicing large multiplication problems, despite the fact that large multiplications are predominantly solved by direct memory retrieval (e.g., Campbell & Xue, 2001; Kirk & Ashcraft, 2001). In contrast, because small additions (e.g., $3 + 4$) have high memory strength, we expected strong RIF of small additions following practice of their multiplication counterparts.

Retrieval-Dependent RIF of Arithmetic Facts

RIF could arise from inhibition of competitors (e.g., Anderson, Bjork, & Bjork, 2000; Bäuml, 2002; Bäuml & Aslan, 2004; Ciranni & Shimamura, 1999; Shivde & Anderson, 2001) or from interference that occurs because strengthening a target memory blocks retrieval of related items without active inhibition (e.g., Camp, Pecher, & Schmidt, 2007; Censabella & Noël, 2004; Jakab & Raaijmakers, 2009; see also MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003). According to Anderson et al. (2000), RIF arising from inhibition should be retrieval dependent, because competition from related facts would occur only when retrieval is required. This reflects the principle of interference dependence of RIF (Anderson, 2003), which holds that inhibition of competitors (and consequent RIF) is generated only when there is retrieval competition. There are several lines of converging evidence for this (e.g., RIF is weak or absent if a practiced memory is very strong, or if a competing memory is very weak; RIF occurs with retrieval practice but not study practice; see Anderson, 2003). Studying a fact without retrieval does not require resolution of interference from competitors; consequently, competitors are activated but not inhibited because they do not interfere with study. Once a retrieval attempt of the target memory occurs, however, then competitors are a source of interference and are inhibited. Studying but not retrieving a fact, however, would increase its memory strength and could produce RIF by blocking or diluting competitor activation without active inhibition. Therefore, if RIF of arithmetic facts reflects interference it should be observed following either study or retrieval practice, but if RIF depends upon active inhibition it should be observed only following retrieval practice and not study practice.

Experiment 1

To investigate the foregoing issues of RIF in number-fact memory, participants in Experiment 1 either retrieved (e.g., $2 \times 5 = ?$) or studied ($2 \times 5 = 10$) multiplication facts for six blocks. In contrast, Campbell and Phenix (2009) used 40 blocks of practice, far more than the handful of practice trials that is common in RIF research. The six blocks of practice used in Experiment 1 should, in principle, be sufficient to produce robust RIF, on the basis of past research (see Levy & Anderson, 2002). Furthermore, the addition posttest following multiplication practice included two blocks in which both the MP-addition set (i.e., problems whose multiplication counterparts were practiced) and the MU-addition set (i.e., problems whose multiplication counterparts were unpracticed) were tested. For both the retrieval-practice and study groups, the two addition posttest blocks were separated by a block of multiplication retrieval trials involving both MP- and MU-multiplication problems. If RIF is retrieval dependent, the intervening multiplication retrieval block was expected to produce RIF for all corresponding addition items in the final addition test block, and thereby eliminate differences between MP and MU problems (i.e., RIF effects) observed in the first test block.

The foregoing theoretical and empirical observations afforded a highly specific prediction for RIF in the Problem Set (MP addition vs. MU addition) × Group (retrieval practice vs. study practice) × Problem Size (small vs. large) × Block (1 vs. 2) design. Specifically, we expected to observe an RT deficit for MP additions relative to MU additions only for the retrieval-practice group in the first block of the posttest and only for small addition problems. This prediction corresponds to a specific four-way interaction in the RT analysis. Furthermore, if RIF of addition facts occurs because multiplication retrieval practice reduces the probability that MP additions are solved by direct memory retrieval, then we should also observe the corresponding four-way interaction on reported retrieval usage.

Method

Participants. Thirty-six volunteers participated for bonus marks in their introductory psychology course at the University of Saskatchewan. The recruitment description of the experiment identified it as a study of simple numerical skills. The sample included 30 women and six men, 35 were right handed, and all indicated normal or corrected-to-normal vision. Ages ranged from 17 to 41 years ($M = 20.0$). Odd-numbered participants were assigned to the study-practice group and even-numbered to the retrieval-practice group.

Apparatus and stimuli. Stimuli appeared on two high-resolution monitors connected to a Microsoft Windows-based PC, with one monitor viewed by the experimenter and the other by the participant. The participant sat approximately 50 cm from the monitor and wore a lapel microphone that activated a relay switch connected to the computer's serial port. The sound-activated relay controlled a software clock accurate to ±1 ms.

Addition problems ranged from $2 + 2$ to $9 + 9$ and multiplication problems from 2×2 to 9×9. All stimuli appeared as white characters against a dark background, and characters were approximately 3 mm wide and 7 mm high. Problem operands appeared as Arabic digits separated by the operation sign (+ or ×) with adjacent spaces (e.g., 4×9 or $4 + 9$). Multiplication equations for study practice included an equals sign and the correct product with adjacent spaces around the equals sign (e.g., $4 \times 9 = 36$). Problems were displayed in horizontal orientation.

There are 36 possible pairs composed from the operands 2 through 9 when commuted pairs (e.g., $3 + 8$ and $8 + 3$) are counted as one problem. The set includes 8 "ties" (e.g., $2 + 2$, $3 + 3$, etc.) and 28 nonties (e.g., $2 + 3$). An operand order for each nontie pair (e.g., $2 + 3$ or $3 + 2$) was selected at random and was used for both operations throughout the experiment. The set of 36 operand pairs was divided into two matched sets of 18. Each set contained four tie and 14 nontie problems; there were four problems involving each of the operands 2 through 9; and each set contained five problems composed of even operands ($4 + 8$), five problems composed of odd operands ($3 + 7$), and eight problems composed of an odd and even operand ($4 + 7$). Set 1 consisted of the following: $2 + 2$, $2 + 5$, $3 + 4$, $2 + 6$, $3 + 5$, $4 + 4$, $3 + 6$, $2 + 9$, $4 + 7$, $3 + 9$, $4 + 8$, $5 + 7$, $5 + 8$, $6 + 7$, $6 + 8$, $7 + 7$, $8 + 9$, and $9 + 9$. Set 2 consisted of the following: $2 + 3$, $2 + 4$, $3 + 3$, $2 + 7$, $4 + 5$, $2 + 8$, $3 + 7$, $4 + 6$, $5 + 5$, $3 + 8$, $5 + 6$, $6 + 6$, $4 + 9$, $5 + 9$, $6 + 9$, $7 + 8$, $7 + 9$, and $8 + 8$. Multiplication counterparts were created by substituting the times sign (×) for the plus sign (+).

Design. The experiment had three phases. In the pretest, participants received one block of the 36 addition problems including both MP and MU sets. Next, in the practice phase, there were six blocks of the 18 multiplication problems involving either Set 1 or Set 2, with set counterbalanced across participants. The multiplication set practiced was the MP set and the set unpracticed was the MU set. During the practice phase, participants in the retrieval group were instructed to "state the correct answer aloud" for each problem (e.g., for 2×5 say "ten"), whereas those in the study group were instructed to "silently read each equation and then say the answer out loud" (e.g., for $2 \times 5 = 10$ say "ten"). The final, posttest phase consisted of a block of all 36 addition problems (i.e., both the MP and MU sets), a block of all 36 multiplication problems with retrieval instructions, and a final block of the 36 addition problems. Problem order was random in each block.

Procedure. The study took place in a quiet room with an experimenter present and required about 30 min. Instructions described the three phases. For the pretest and posttest trials, participants were instructed to state the correct answer quickly without sacrificing accuracy. Prior to the addition posttest blocks, instructions for strategy reports appeared on the monitor and were read aloud by the experimenter as follows:

> After each problem please indicate how you solved the problem by choosing from among the following strategies: Say TRANSFORM if you used a procedure or knowledge of another related problem. Say COUNT if you used a strategy based on counting one by one. Say REMEMBER if you recalled the answer directly without any intermediate steps. Choose OTHER if you used some other strategy or are uncertain.

Participants also received a sheet of strategy descriptions that included examples not involving problems used in the experiment.

Each trial began with the presentation of a 1-s central fixation dot. The problem or equation then appeared with the times sign or plus sign at fixation. Timing began with the onset of the stimulus and continued until the participant's verbal response stopped the timer. When the response (or any sound) was detected, the stimulus was instantly removed from the screen. This allowed the experimenter to identify trials on which the microphone failed to detect response onset and mark them as spoiled. On addition trials in the posttest, participants were prompted to report their strategy immediately after their arithmetic answer, which the experimenter recorded with a button press. On all trials, the experimenter entered the participant's arithmetic response, and then the fixation dot immediately appeared to signal the start of the next trial. Participants received no feedback regarding speed or accuracy.

Results

A total of 206 pretest, practice phase, or posttest RTs (2.3%) were marked as spoiled by the experimenter and excluded from analysis. To define problem size, problems with a sum ≤ 10 were small and those with a sum > 10 were large (LeFevre et al., 1996). We used the same size definition for addition and multiplication. We first present analyses of multiplication performance and the addition pretest data. We then present the addition posttest data to examine RIF effects. Significance levels were less than or equal to .001 unless stated otherwise.

Multiplication practice phase and posttest block. Interpretation of the retrieval-group versus study-group manipulation requires evidence of similar degrees of strengthening of the practiced multiplication facts in the retrieval and study conditions. Otherwise, if greater RIF is observed with retrieval than study practice, this might reflect strength-based interference rather than inhibition. We examined the multiplication practice data and also compared performance of the practiced and unpracticed problems in the multiplication posttest block to assess this.

Median RT for correct answers during multiplication practice received a Group (retrieval vs. study) × Size (small vs. large) × Block analysis of variance (ANOVA) with pairs of successive blocks combined. Mean RT decreased across blocks (952 ms, 917 ms, 902 ms), $F(2, 68) = 3.1$, $MSE = 15{,}069$, $p = .05$, $\eta_p^2 = .08$. The Group × Size effect, $F(1, 34) = 9.8$, $MSE = 17{,}212$, $p = .004$, $\eta_p^2 = .22$, reflected a larger problem-size effect for the retrieval group (+148 ms; small problems 794 ms, large 942 ms) than the study group (+36 ms; small problems 961 ms, large 997 ms). As would be expected, problem difficulty (i.e., small vs. large problems) had a larger effect when answers had to be retrieved than when presented answers simply needed to be stated aloud. Overall, however, the groups spent a similar amount of time on average processing practice stimuli (retrieval 868 ms, study 979 ms), $F(1, 34) = 2.8$, $MSE = 236{,}870$, $p = .10$, $\eta_p^2 = .08$. The study group made virtually no errors stating the presented products (0.04%), which precluded a full factorial analysis of multiplication practice errors. The retrieval group made 8.0% errors in the first pair of practice blocks, 4.5% in the second, and 3.9% in final pair of practice blocks. Accuracy for the retrieval group was very high for both small (97.9%) and large problems (91.1%) during the practice phase. The two groups were very accurate during practice and similar in practice time per problem, but did they exhibit similar performance on the multiplication posttest block?

For the multiplication posttest, median RT for correct answers and percentage of errors received a Group × Size × Set (practiced vs. unpracticed) ANOVA. The corresponding means appear in Table 1. There were no significant effects in the RT analysis involving the group factor (all ps $\geq .09$). The retrieval group presented a 212-ms mean RT advantage for practiced (850 ms) relative to unpracticed problems (1,062 ms), $F(1, 17) = 53.2$, $MSE = 15{,}175$, $\eta_p^2 = .76$. The study group presented a 133-ms mean RT advantage for practiced (1,015 ms) compared with unpracticed problems (1,148 ms), $F(1, 17) = 13.0$, $MSE = 24{,}736$, $p = .002$, $\eta_p^2 = .43$. The Group × Set effect was not significant, $F(1, 34) = 2.8$, $MSE = 19{,}956$, $p = .10$, $\eta_p^2 = .08$. The corresponding analyses of percentage of errors indicated no significant effects involving group (all ps $\geq .14$). Overall, there were fewer errors for practiced (4.7%) than unpracticed problems (9.0%), $F(1, 34) = 23.8$, $MSE = 28.6$, $\eta_p^2 = .41$. Thus, there was no evidence that multiplication posttest performance differed between the retrieval-practice and study-practice conditions.

Addition pretest performance. The addition pretest block was evaluated to ensure there were no group or problem set performance differences prior to multiplication practice. Median RT for correct addition problems and percentage of error in the pretest block received a Group (retrieval vs. study) × Set (MP addition vs. MU addition) × Size (small vs. large) ANOVA. The means appear in Table 2. In the RT analysis, there was the standard effect of problem size with small problems (813 ms) yielding faster RTs than large problems (970 ms), $F(1, 34) = 44.5$, $MSE = 20{,}034$, $\eta_p^2 = .57$. There were no other significant effects on pretest RTs (all ps $\geq .19$). Similarly, the error analysis indicated only a

Table 1
Mean Correct RT and Percentage of Errors (E%) for the Multiplication Posttest as a Function of Group, Problem Size, and Problem Set in Experiment 1

	RT		E%	
Problem size	MU	MP	MU	MP
Retrieval-practice group				
Small	936	770	4	2
Large	1,189	931	11	6
Study-practice group				
Small	997	889	5	3
Large	1,299	1,141	17	8

Note. RT = response time in milliseconds; MU = multiplication problems unpracticed; MP = multiplication problems practiced.

main effect of problem size, with fewer errors on small (2.6%) than large problems (7.8%), $F(1, 34) = 14.0$, $MSE = 68.0$, $p = .001$, $\eta_p^2 = .29$; all other $ps \geq .50$.[1] Thus, there was no evidence from the ANOVAs that addition performance differed between the practice groups or between MP- and MU-addition problems prior to multiplication practice.

Addition posttest RT. Median RT for correct addition problems in the posttest blocks received a Group × Set × Size × Block (1 vs. 2) ANOVA. The corresponding means appear in Figure 1. As expected, small addition problems were answered faster on average (886 ms) than large addition problems (1,040 ms), $F(1, 34) = 28.0$, $MSE = 61{,}308$, $\eta_p^2 = .45$; however, this problem-size effect was smaller for the retrieval-practice group (89 ms) than the study-practice group (219 ms), $F(1, 34) = 5.0$, $MSE = 61{,}308$, $p = .03$, $\eta_p^2 = .13$. The only other effect was the four-way Group × Set × Block × Size interaction, $F(1, 34) = 4.3$, $MSE = 10{,}869$, $p = .05$, $\eta_p^2 = .11$. This effect reflected a Group × Block × Set interaction for small problems, $F(1, 34) = 6.1$, $MSE = 6{,}312$, $p = .02$, $\eta_p^2 = .15$, but not for large problems, $F(1, 34) = 0.9$, $MSE = 13{,}134$, $p = .34$, $\eta_p^2 = .03$. Indeed, there were no effects of group or problem set for large problems (all $ps \geq .14$); thus, as expected, practicing large multiplication problems did not interfere with their addition counterparts.

For small problems in Block 1, the retrieval-practice group presented a –94-ms RIF effect (MU 844 ms, MP 938 ms), $t(17) = -3.1$, $SE = 31.0$, $p = .007$, $\eta^2 = .36$, whereas the study-practice group did not present a significant difference (26 ms; MU 912 ms, MP 886 ms), $t(17) = 1.0$, $SE = 26.1$, $p = .34$, $\eta^2 = .05$. This produced a robust Group × Set effect on small problem RTs in Block 1, $F(1, 34) = 8.9$, $MSE = 7{,}384$, $p = .005$, $\eta_p^2 = .21$. In contrast, in Block 2, both groups produced weak evidence of RIF for small problems (–25 ms for the retrieval-practice group and –34 ms for the study-practice group), $F(1, 34) = 2.5$, $MSE = 6{,}380$, $p = .13$, $\eta_p^2 = .07$, for the main effect of set, with no evidence of a Group × Set interaction, $F(1, 34) = 0.1$, $MSE = 6{,}380$, $p = .80$, $\eta_p^2 = .002$. Thus, despite the potential complexity of interpreting a four-way interaction, the four-way effect here was straightforward: For the retrieval group only, multiplication practice selectively interfered with performance of small addition problems in Block 1 of the posttest.

Reported retrieval for posttest addition. Overall, participants reported memory retrieval (i.e., selected the remember strategy) on 74.5% of trials, transformation on 12.7%, counting on 11.9%, and "other" strategy on 0.9% of trials. The percentage of retrieval reported for addition was similar to what has been found in previous studies with North American university students (76% in Campbell & Xue, 2001; 73% in Geary, 1996; 66% in Hecht, 1999; 71% in LeFevre et al., 1996). Mean percent use of retrieval in the 16 cells of the Group × Set × Block × Size design is presented in Figure 2. Across the 16 cells in Figures 1 and 2, mean percentage of retrieval and mean RTs for correct trials are correlated at –.92 ($p < .001$). The negative correlation between RT and retrieval rate occurs because retrieval generally is faster than a

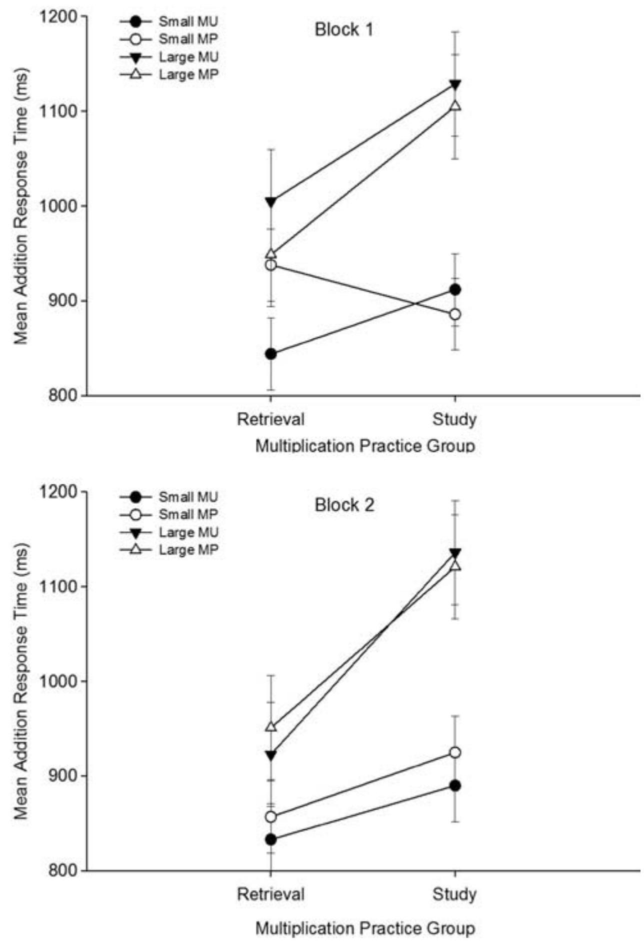

Figure 1. Mean response time in Experiment 1. Error bars are the 95% within-subject confidence intervals based on separate analyses of variance for small and large problems (Jarmasz & Hollands, 2009). MU = multiplication problems unpracticed; MP = multiplication problems practiced.

Table 2
Mean Correct RT and Percentage of Errors (E%) for the Addition Pretest as a Function of Group, Problem Size, and Problem Set in Experiment 1

	RT		E%	
Problem size	MU	MP	MU	MP
Retrieval-practice group				
Small	768	791	1	3
Large	912	930	7	7
Study-practice group				
Small	866	828	3	3
Large	1,023	1,017	9	9

Note. RT = response time in milliseconds; MU = multiplication problems unpracticed; MP = multiplication problems practiced.

[1] Separate analysis of *operation errors* (e.g., 2 + 5 = 10) was precluded here and for posttest trials in both experiments because of empty cells with means and variances of 0. As in previous research (e.g., Campbell, 1994), operation errors were more likely for small addition and multiplication problems than for large problems. There were also more operation errors made on MP-addition problems than MU-addition problems in the posttest in both experiments, but no evidence that this differed between the retrieval-practice and study-practice groups.

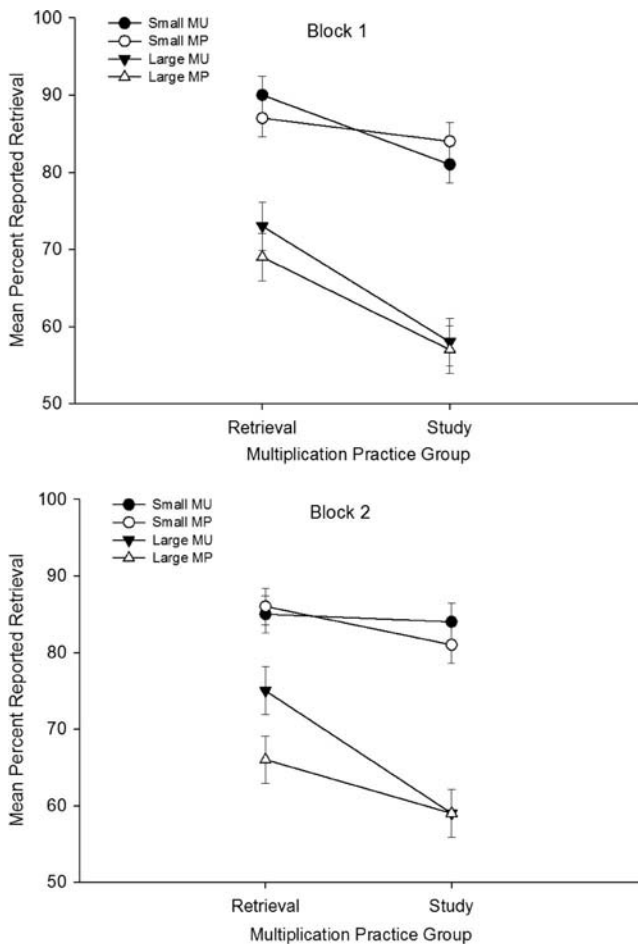

Figure 2. Mean percent reported retrieval in Experiment 1. Error bars are the 95% within-subject confidence intervals based on separate analyses of variance for small and large problems (Jarmasz & Hollands, 2009). MU = multiplication problems unpracticed; MP = multiplication problems practiced.

procedural strategy (Campbell & Xue, 2001; LeFevre et al., 1996); consequently, mean RT decreases as the proportion of retrieval trials increases. The four-factor ANOVA of retrieval percentages indicated that retrieval was reported far more for small addition problems (84.6%) than large problems (64.5%), $F(1, 34) = 48.2$, $MSE = 602$, $\eta_p^2 = .59$ (see also Campbell & Xue, 2001; LeFevre et al., 1996). The only other effect was the four-way Group × Set × Block × Size interaction, $F(1, 34) = 8.8$, $MSE = 29.7$, $p = .005$, $\eta_p^2 = .21$. As Figure 2 shows, the retrieval group reported less use of retrieval for large MP- than large MU-addition problems in Block 2, but otherwise percentage retrieval between MU and MP conditions did not differ across conditions. Thus, the RIF effects observed in RT were not obviously linked to reported use of retrieval.

Addition posttest errors. The overall error rate on addition problems was 4.0%. Mean percentage of errors received the same four-factor ANOVA used in the preceding analyses. This revealed two main effects only: There were fewer errors for small (2.5%) than large problems (5.5%), $F(1, 34) = 6.7$, $MSE = 100.8$, $p = .01$, $\eta_p^2 = .17$, and fewer errors for MU (3.0%) than MP problems (5.0%), $F(1, 34) = 5.2$, $MSE = 51.0$, $p = .03$, $\eta_p^2 = .13$.

Discussion

The results of Experiment 1 illustrated two important phenomena of RIF of arithmetic facts. First, RIF effects on RT were observed only with retrieval practice and not with study practice, which converges with previous research (e.g., Anderson et al., 2000; Bäuml, 2002; Campbell & Phenix, 2009) to support the conclusion that RIF arises from inhibition of competitors in memory and not just blocking or some other form of retrieval interference. Both groups presented robust learning of the practiced multiplication facts and did not present statistically different improvements for practiced relative to unpracticed multiplication facts. Therefore, RIF for the retrieval group, but not the study group, cannot be attributed to different amounts of multiplication strengthening during the practice phase. Furthermore, because the MP and MU sets both included the operands from 2 through 9 equally, the RIF measured must have occurred at the level of individual facts composed of a unique combination of operands and was not a result of RIF of the families of facts associated with the practiced operands.

Second, the finding that robust RIF occurred for small addition problems, and not large addition problems, implies that the principle of interference dependence applies to RIF in number-fact memory (e.g., Anderson, 2003; Norman et al., 2007). Small addition problems generally have high memory strength and would be strong competitors for their multiplication counterparts, particularly after being strengthened in the addition pretest. Consequently, we would expect small addition problems to attract strong inhibition during multiplication retrieval practice.

For the retrieval group, RIF expressed in RT was robust in Block 1 of posttest addition, whereas in Block 2 the difference between MP and MU addition was not significant. We predicted that the intervening block of multiplication retrieval trials involving both MP- and MU-multiplication problems would create RIF for MU-addition problems and reduce the difference between MP and MU problems for the retrieval group. Addition performance in Block 2, however, also would reflect the facilitative influence of the first addition block, which would work against RIF. This trade-off would explain why mean MU-addition RT was similar across blocks. Successful retrieval in Block 1 could also weaken the RIF accumulated by MP-addition problems during multiplication retrieval practice, allowing them to speed up considerably in Block 2.

We measured RIF after six multiplication practice blocks, far less than the 40 practice blocks used in the Campbell and Phenix (2009) experiment. Nonetheless, the effect was robust. Indeed, RIF in the retrieval-practice condition was sufficiently strong in posttest Block 1 to slow mean RT for small MP problems to be equivalent to that for large MP problems (938 ms and 949 ms, respectively). In other words, RIF practically eliminated the problem-size effect for MP-addition problems in Block 1. This would have contributed to the smaller problem-size effect on RT for the retrieval-practice group compared with the study-practice group. It is also possible, however, that large MP-addition problems (949 ms) benefited to some extent from retrieval practice relative to large MU problems (1,005 ms) in Block 1. For example, practice of large multiplication problems could prime their addition counterparts which, in the absence of RIF, might facilitate addition performance (Campbell & Phenix, 2009).

Finally, mean RT and mean percentage of reported retrieval for addition were highly correlated across the 16 cells of Experiment 1 ($r = -.92$). Nonetheless, there was no clear evidence from the ANOVA of reported retrieval that multiplication practice affected retrieval usage for corresponding addition problems. The retrieval group reported less retrieval for large MP than MU problems in Block 2, but this is at most weak evidence for RIF given that there was no corresponding effect on RT in Block 2. Thus, RIF was clearly expressed in RT but not in reported retrieval usage. One possibility is that retrieval self-reports are not a sufficiently sensitive measure of retrieval usage (Thevenot et al., 2010). Another possibility is that retrieval strength for small additions is sufficient to support direct memory retrieval even under conditions of RIF.

Experiment 2

RIF can occur in both episodic (e.g., Ciranni & Shimamura, 1999) and semantic memory tasks (e.g., Johnson & Anderson, 2004). Experiment 2 addressed whether the RIF effects in Experiment 1 reflected episodic or semantic memory. Campbell and Phenix (2009) argued that RIF of addition by multiplication practice illustrated RIF in semantic memory rather than episodic memory. This is consistent with evidence that arithmetic facts are stored in long-term memory in categorical structures organized by problem operands (i.e., the operands function as category cues; Ashcraft, 1992; Campbell, 1995; Verguts & Fias, 2005). For example, most simple multiplication errors involve a multiple of one of the factors (e.g., $4 \times 8 = 36$), with the probability of a specific factor-related error declining with numerical distance. The distance effect on errors observed in both simple multiplication and addition (e.g., Campbell, 1995) indicates that problem operands are encoded as semantic quantities, which implies a semantic component in arithmetic-fact retrieval. Nonetheless, participants do not necessarily rely on semantic memory when problems are repeated within an experimental session. For example, participants might recall a previous encounter with a specific problem and use this episodic memory as the basis of performance. Consequently, the addition pretest used in Experiment 1 opens the possibility that the RIF observed was a phenomenon of episodic memory rather than semantic memory. Experiment 2 included a replication of the practice and posttest phases from Experiment 1, but there was no addition pretest. Thus, if we observe RIF in Experiment 2 when the addition problems were encountered for the first time in the posttest, this effect presumably reflects RIF of semantic memory, as there would not be recent episodic memories of addition facts to mediate performance.

Experiment 2 also was designed to use RIF to address a long-standing debate about the source of format effects (e.g., 3×4 vs. three $\times$ four) on arithmetic performance (e.g., Campbell, 1994; McCloskey et al., 1991; McCloskey & Macaruso, 1995; Noël, Fias, & Brysbaert, 1997). Much research has demonstrated that arithmetic performance with written-word operands is substantially slower, is more error prone, and relies more on procedural strategies than when problems are in digit format. Furthermore, all of these effects are usually exaggerated for large problems relative to small problems (e.g., Campbell & Alberts, 2009; see also Campbell & Epp, 2005, for a review of this literature). The debate concerns the origin of these effects. The single-format hypothesis holds that different surface forms access a common internal memory structure and that format effects arise only during input or output (e.g., Blankenberger & Vorberg, 1997; McCloskey et al., 1991; Noël et al., 1997). The multiple-format hypothesis holds that different numeral surface forms may recruit distinct processes (Campbell, 1994, 1999). There is good evidence that the written-word format reduces direct memory retrieval for simple addition and increases use of procedural strategies (Campbell & Alberts, 2009; Campbell & Fugelsang, 2001); consequently, digit and word-format problems often do recruit different solution processes. Word-format costs relative to digit format are still observed, however, when only trials reported as retrieval based are analyzed (Campbell & Alberts, 2009). This raises the possibility that arithmetic-fact retrieval with digit versus word format is based on distinct long-term memory structures.

Experiment 2 investigated this by examining RIF for addition facts tested in digit format after retrieval practice of multiplication facts in digit format (digit-retrieval group), after retrieval practice of multiplication facts in word format (word-retrieval group), and after study practice of multiplication facts in digit format (digit-study group). We expected no RIF for the digit-study group as in Experiment 1, given the evidence that RIF in number-fact memory is retrieval dependent. With respect to the retrieval-practice groups, if the memory network subserving addition and multiplication retrieval is format independent, then we would observe RIF for addition problems in digit format regardless of whether multiplication retrieval practice was in digit format or word format. In contrast, if the retrieval network is format specific, then we would observe RIF of digit-format addition when multiplication was practiced in digit format but not when it was practiced in word format.

Method

Thirty-six volunteers were recruited as in Experiment 1. The three practice groups (i.e., digit retrieval, word retrieval, and digit study) were created by cycling through the three conditions as participants entered the study until there were 12 in each group. We replaced a participant in the digit-retrieval group whose mean RT for small addition cells was 4.0 *SD* above the grand mean for small addition problems. Additionally, as it was critical that the three groups achieve similar multiplication learning during practice, we also replaced five digit-study participants who showed no advantage in posttest multiplication for practiced over unpracticed problems. The necessity to replace some study-group participants probably reflected a change in instructions. In Experiment 1, the study group was instructed to "silently read each equation and then say the answer out loud," but this was reworded in Experiment 2 to "attend to each equation and then say the answer out loud." This change had the unintended consequence of reducing effective study for some participants. The final sample included 26 women and 10 men, 34 were right handed, and all indicated normal or corrected-to-normal vision. Ages ranged from 17 to 26 years ($M = 19.2$).

Apart from the change of instructions to the study group, the apparatus, stimuli, and procedure were identical to those in Experiment 1, except that there was no addition pretest and the word-retrieval group received their multiplication practice problems with operands in lowercase English (e.g., three × two).

Results

A total of 260 practice phase or posttest RTs (3.3%) were marked as spoiled by the experimenter and excluded from analysis. Presentation of the results is organized as in Experiment 1.

Multiplication practice phase and posttest block. Multiplication practice trials were analyzed as in Experiment 1. Mean practice RT was fastest for the digit-study group (573 ms) followed by the digit-retrieval (898 ms) and word-retrieval groups (1,220 ms), $F(2, 33) = 39.2$, $MSE = 192{,}456$, $\eta_p^2 = .70$. This pattern reflects the fact that the revised instructions for the study group led to fast study trials relative to retrieval. Additionally, as seen in previous research (e.g., Campbell, 1994; Campbell & Alberts, 2009), word-format problems were answered more slowly than digit-format problems. The Group × Size effect, $F(2, 33) = 13.8$, $MSE = 20{,}168$, $\eta_p^2 = .46$, reflected a substantial problem-size effect for the word-retrieval (+262 ms) and digit-retrieval groups (+189 ms) but not the digit-study group (+19 ms). The Group × Block effect, $F(4, 66) = 2.9$, $MSE = 6{,}622$, $p = .03$, $\eta_p^2 = .15$, reflected substantial speed-up across practice blocks for the word-retrieval (–110 ms between Blocks 1–2 and Blocks 5–6) and digit-retrieval groups (–91 ms) but not the digit-study group (–12 ms). The overall multiplication error rate during practice was 5.6% for word retrieval, 4.6% for digit retrieval, and 0.5% for digit study, $F(2, 33) = 10.0$, $MSE = 52.2$, $\eta_p^2 = .38$, but there were no other effects involving the group factor ($ps \geq .22$). For the retrieval groups, mean practice accuracy was 96.8% for small problems and 93.0% for large problems. Thus, the rates of successful retrieval during practice were very high for both small and large multiplication problems.

Median RT and percentage of errors in the posttest multiplication block were analyzed as in Experiment 1. The means appear in Table 3. The only RT effect involving the group factor that approached significance was the Group × Set × Size interaction, $F(2, 33) = 3.0$, $MSE = 11{,}742$, $p = .06$, $\eta_p^2 = .15$. This occurred because the word-retrieval group produced a larger problem-size effect for MU than MP problems, $F(1, 11) = 6.2$, $MSE = 13{,}602$, $p = .03$, $\eta_p^2 = .36$, whereas neither the digit-retrieval nor digit-study group presented this Set × Size interaction ($Fs < 1$). Most important, all three groups presented a robust RT advantage for practiced relative to unpracticed multiplication problems: For the digit-retrieval group the practice effect was –188 ms (practiced 868 ms, unpracticed 1,056 ms), $F(1, 11) = 30.1$, $MSE = 13{,}826$, $\eta_p^2 = .74$; for the word-retrieval group it was –116 ms (practiced 957 ms, unpracticed 1,073 ms), $F(1, 11) = 22.1$, $MSE = 7{,}284$, $p = .001$, $\eta_p^2 = .67$; and for the digit-study group it was –94 ms (practiced 897 ms, unpracticed 991 ms), $F(1, 11) = 8.3$, $MSE = 12{,}725$, $p = .02$, $\eta_p^2 = .43$. The corresponding analyses of posttest multiplication errors indicated no significant effects of group (all $ps \geq .08$). The mean error rates for word retrieval, digit retrieval, and digit study were 5.7%, 5.9%, and 4.8%, respectively. The multiplication posttest results thus indicated that, although the study group spent less time than the two retrieval groups processing problems during the practice phase, they achieved robust strengthening of the practiced multiplication problems.

Table 3
Mean Correct RT and Percentage of Errors (E%) for Multiplication Posttest as a Function of Group, Problem Size, and Problem Set in Experiment 2

	RT		E%	
Problem size	MU	MP	MU	MP
Digit-retrieval group				
Small	969	757	2	1
Large	1,143	980	16	4
Digit-study group				
Small	839	778	4	1
Large	1,143	1,017	8	3
Word-retrieval group				
Small	884	851	3	1
Large	1,262	1,062	14	4

Note. RT = response time in milliseconds; MU = multiplication problems unpracticed; MP = multiplication problems practiced.

Addition RT. RT for correct addition problems (see Figure 3) was analyzed as in Experiment 1. Small additions presented faster mean RTs (878 ms) than large additions (1,096 ms), $F(1, 33) = 35.6$, $MSE = 96{,}188$, $\eta_p^2 = .52$, and addition RT was faster in Block 2 (968 ms) than Block 1 (1,007 ms), $F(1, 33) = 7.2$, $MSE = 15{,}507$, $p = .01$, $\eta_p^2 = .18$. The only other significant effect was the Group × Set × Size interaction, $F(2, 33) = 6.0$, $MSE = 15{,}082$, $p = .006$, $\eta_p^2 = .27$. The three-way effect reflected a significant Group × Set interaction for small problems, $F(2, 33) = 5.6$, $MSE = 5{,}031$, $p = .008$, $\eta_p^2 = .25$, but not for large problems, $F(1, 33) = 2.3$, $MSE = 29{,}710$, $p = .11$, $\eta_p^2 = .13$. As in Experiment 1, there were no significant effects involving group or set for large problems ($ps > .1$).

For small addition problems, the digit-retrieval group presented RIF, with longer RTs for MP (921 ms) than MU addition (880 ms), $t(11) = 2.2$, $SE = 19.0$, $p = .05$, $\eta^2 = .30$. The word-retrieval group also presented longer addition RTs for MP (961 ms) than MU problems (879 ms), $t(11) = 3.2$, $SE = 25.9$, $p = .009$, $\eta^2 = .48$, thereby demonstrating cross-format RIF. Although there were no interactions with block ($ps \geq .15$), a separate analysis of the retrieval groups indicated robust RIF (i.e., MU addition − MP addition) for small problems only in Block 1, $F(1, 22) = 9.9$, $MSE = 8{,}824$, $p = .005$, $\eta_p^2 = .31$, and not in Block 2, $F(1, 22) = 1.6$, $MSE = 10{,}759$, $p = .22$, $\eta_p^2 = .07$. This pattern replicated the results for the retrieval group in Experiment 1 and presumably owes to the RIF of the MU-addition facts from the intervening multiplication retrieval block and also to the addition practice in Block 1 weakening the accumulated RIF for MP additions. In contrast, as also shown in Figure 3, the digit-study group presented similar mean RTs for small MP- (808 ms) and MU-addition problems (822 ms), $F(11) = 1.0$, $MSE = 2{,}740$, $p = .36$, $\eta^2 = .08$.

Reported retrieval for addition. Overall, participants reported memory retrieval on 76.2% of trials, transformation on 11.4%, counting on 11.0%, and "other" strategy on 1.3% of trials. Mean percent retrieval for the Group × Set × Block × Size cells appears in Figure 4. Across the 24 cells in Figures 3 and 4, mean percentage of retrieval and mean RT were correlated at –.90 ($p < .001$); thus, as in Experiment 1, there was a strong relation between mean RT and reported retrieval usage. An ANOVA indicated that retrieval was reported more for small problems (88.8%) than large

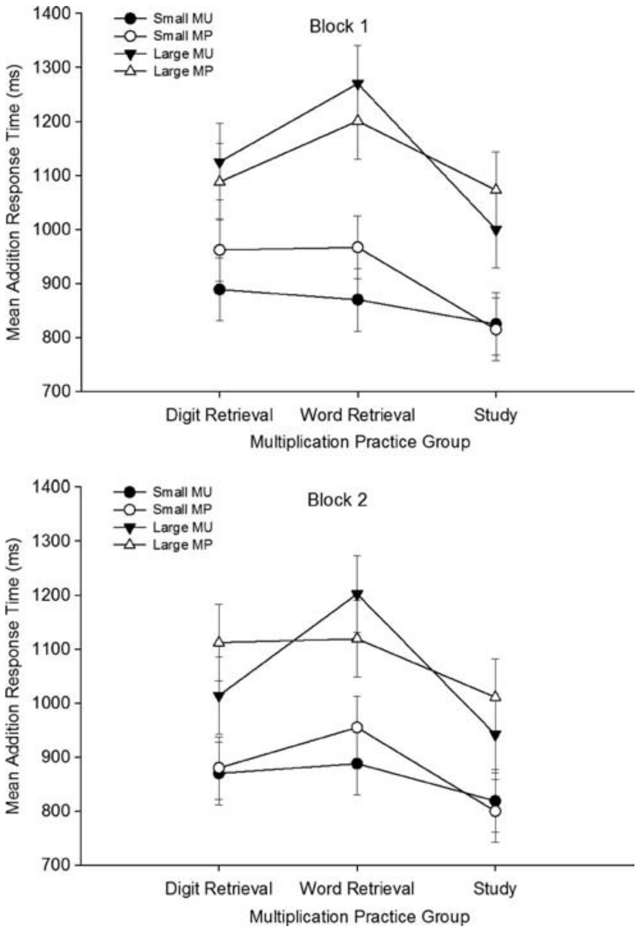

Figure 3. Mean response time in Experiment 2. Error bars are the 95% within-subject confidence intervals based on separate analyses of variance for small and large problems (Jarmasz & Hollands, 2009). MU = multiplication problems unpracticed; MP = multiplication problems practiced.

problems (63.7%), $F(1, 33) = 49.4$, $MSE = 916.7$, $\eta_p^2 = .60$. There also was evidence for a Group × Size × Set interaction, $F(2, 33) = 3.1$, $MSE = 87.1$, $p = .06$, $\eta_p^2 = .16$, but decomposing this into separate Group × Set analyses for small and large problems did not reveal different patterns of significant effects. Thus, as in Experiment 1, there was no clear evidence of RIF effects in the retrieval reports.

Addition errors. The overall error rate on addition problems was 3.1%. Mean percentage of errors received the same four-factor ANOVA used in the preceding analyses, but there were no significant effects.

Discussion

Both the digit-retrieval and word-retrieval practice groups presented RIF in mean RT for small MP-addition problems relative to MU-addition problems. As there was no addition pretest, participants could not have relied on recent episodic memory representations to answer addition problems in Block 1. We suggest therefore that semantic retrieval of the addition facts was inhibited. A semantic component is implicated in retrieval of arithmetic facts by evidence that problem operands function as category cues, with exemplar activation graded by semantic distance (e.g., Verguts & Fias, 2005). Nonetheless, multiple repetitions of the multiplication facts during the practice phase introduce a possible contribution of episodic retrieval processes in the recruitment of inhibition. The fact that the addition facts did not need to be primed (i.e., by a pretest) in order to attract RIF also indicates that RIF of competing addition facts is an intrinsic process of multiplication fact retrieval. The results support the view that addition and multiplication are stored in an interrelated semantic network and that retrieval competition between related facts has a substantial impact on performance (see also Campbell & Arbuthnott, 2010; Miller & Paredes, 1990; Zbrodoff & Logan, 1986).

Finally, Experiment 2 also provided clear evidence that multiplication practice with operands in word format (e.g., two × three) produced RIF of the corresponding addition problem tested in digit format (2 + 3). This finding indicates that multiplication practice in word format inhibited the addition fact retrieved later via the digit format. This strongly suggests that the two surface forms of

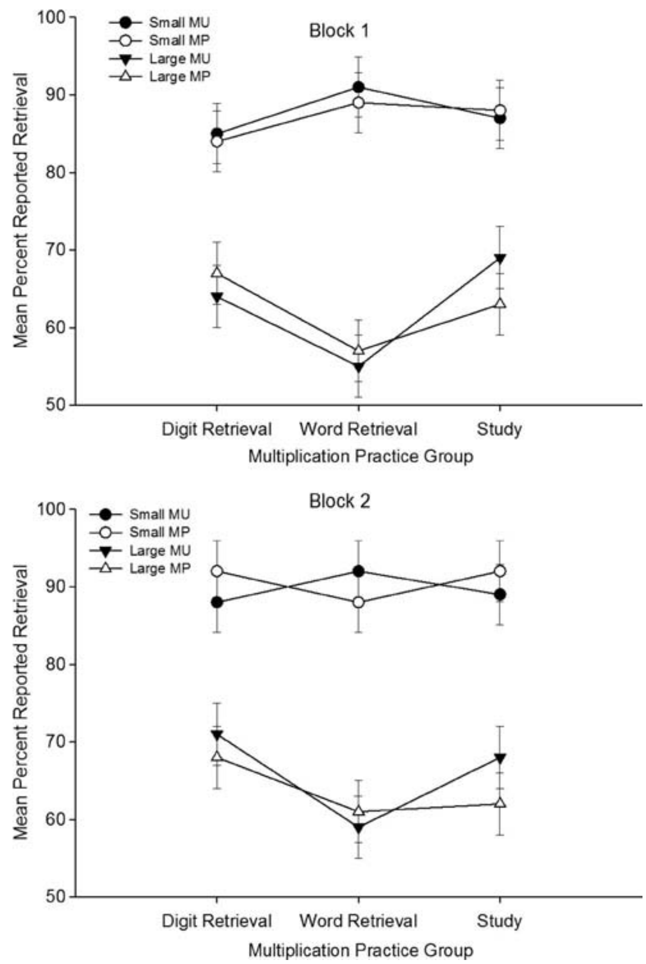

Figure 4. Mean percent reported retrieval in Experiment 2. Error bars are the 95% within-subject confidence intervals based on separate analyses of variance for small and large problems (Jarmasz & Hollands, 2009). MU = multiplication problems unpracticed; MP = multiplication problems practiced.

problems accessed a common network retrieval structure (e.g., McCloskey & Macaruso, 1995).

General Discussion

The results of these experiments support two important principles for RIF in number-fact memory: retrieval dependence and interference dependence (Anderson, 2003). Consistent with a variety of previous RIF research that used the standard retrieval-practice paradigm (e.g., Shivde & Anderson, 2001), RIF was observed only with retrieval practice and not with study practice. Retrieval-dependent RIF is expected if RIF reflects inhibition of competitors rather than only interference or blocking without inhibition. Thus, the results provide support for an active inhibition mechanism in RIF of arithmetic facts. Furthermore, as there was no addition pretest in Experiment 2, addition retrieval performance presumably relied on semantic memory rather than episodic memories. Thus, the present results confirm semantic RIF in arithmetic-fact retrieval. Robust RIF was observed only for small addition problems with sums ≤ 10, which have high memory strength relative to larger simple addition problems. This was expected on the basis of the principle of interference dependence, which holds that inhibition of competitors is generated in response to potential interference (Anderson, 2003; Norman et al., 2007). Given this, we expected robust RIF for small addition problems but not large addition problems because the former would be strong competitors to their multiplication counterparts, whereas the latter would not.

Another purpose of our experiments was to determine if addition RIF reflects item-specific inhibition (e.g., $2 + 5 = 7$ inhibited by practice of $2 \times 5 = 10$) or if it owes to RIF of the family of facts associated with each operand cue (i.e., categorical inhibition; Phenix & Campbell, 2004). In Campbell and Phenix (2009), the MP and MU sets shared no common operand (i.e., category cues) because the two problem sets were constructed from different numbers (2, 5, 7, 8 or 3, 4, 6, 9). Consequently, it was ambiguous whether RIF of addition facts in their experiment reflected item-specific inhibition or categorical inhibition. Here, the two sets included the operands from 2 through 9 equally, which allowed us to isolate item-specific effects (i.e., effects associated with practicing a specific combination of operands such as 2×5). Both of the current experiments produced RIF, which demonstrates that RIF in number-fact memory can occur at the level of individual facts in semantic memory and is not solely a result of categorical inhibition of the family of facts associated with the practiced operands. We propose that retrieval practice of a multiplication fact recruits an inhibitory control process that suppresses the competing addition fact. This does not necessarily imply the formation of inhibitory links from multiplication to addition. Anderson (2003) reviewed studies showing that RIF is observed when an unpracticed cue is used in the final recall test. For example, retrieval practice of red–bl__ (i.e., red–blood) impairs subsequent retrieval of radish (i.e., another red thing) with an unpracticed category cue (food–ra__). This *cue independence* implies that RIF does not require reactivation of the original category cues. Whether RIF in number-fact retrieval is cue independent, however, remains to be determined.

Finally, Experiment 2 also addressed a longstanding issue in the numerical cognition literature: Do different numeral surface forms activate distinct retrieval processes for elementary arithmetic? This question has generated a lively debate over the last two decades (see Campbell & Epp, 2005), but the current results clearly support a common retrieval network for digit and word-format arithmetic: Experiment 2 demonstrated that retrieval practice of multiplication problems in word format (two $\times$ four) produced RIF of the corresponding addition fact tested in digit format ($2 + 4$). This implies that the addition retrieval structure inhibited in the context of word-format multiplication was the same structure subsequently accessed via digit-format addition. Cross-format RIF cannot be easily reconciled with digits and written number words activating entirely different long-term memory structures and instead supports the conclusion that they access a common network of addition and multiplication facts (e.g., McCloskey & Macaruso, 1995; Noël et al., 1997).

Nonetheless, the results do not rule out a version of the multiple-format hypothesis, such as that proposed by Campbell and Alberts (2009; see also Campbell & Epp, 2004). In this view, format-specific problem-encoding processes can interact with the long-term retrieval structures that subserve arithmetic memory. Number facts may be stored as linguistic structures that are associated with semantic quantity codes that represent the numerical magnitude of the operands and answers (e.g., Campbell & Epp, 2004; Dehaene & Cohen, 1997; Dehaene, Piazza, Pinel, & Cohen, 2003). Number-fact retrieval entails the coordinated activation of this collection of associated memory codes and generation of the appropriate response output. Different numeral surface forms, however, may differentially activate components of the semantic and associative structures representing number facts. Campbell and Alberts proposed, for example, that digits more effectively recruit magnitude information for number facts and that written words activate irrelevant reading processes that interfere with retrieving a problem's answer. This interaction between encoding and retrieval processes gives rise to robust format effects on number-fact retrieval (see Campbell, 1994; Campbell & Alberts, 2009; Campbell & Epp, 2004), despite an overlapping representational network for retrieval with digit and word formats.

Conclusions

The current findings highlight the potential importance of RIF to theories of arithmetic memory, demonstrating that it is an intrinsic feature of the semantic networks for simple addition and multiplication facts. Miller and Paredes (1990; see also Lemaire, Barret, Fayol, & Abdi, 1994) proposed that multiplication interferes with addition from the outset of learning and that this competition remains an inherent factor in adults' simple addition performance. The current findings reinforce this conclusion and suggest that RIF may be an important mechanism in arithmetic development. The potential importance of RIF, and its associated literature, to theories of learning and performance of mental arithmetic has not been widely recognized in the cognitive or educational literatures. On the other hand, arithmetic memory could be a fruitful domain for RIF theory, particularly in relation to semantic RIF. Arithmetic affords measures of speed, error characteristics, and strategy use that have been studied extensively and therefore offers a rich empirical and theoretical foundation of research to relate to the extant RIF literature. Arithmetic affords manipulation of both category and item practice and may be tested in recall ($3 + 2 = ?$) or recognition contexts ($3 + 2 = 6$, true or false?). The present experiments should encourage researchers in both fields to consider how their research areas can mutually inform one another.

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