Cognitive Skill Learning: Age-Related Differences in Strategy Shifts and Speed of Component Operations

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Abstract:

Younger and older adults solved novel arithmetic problems and reported the strategies used for obtaining solutions. Age deficits were demonstrated in the latencies for computing and retrieving solutions and in the shift from computation to retrieval. Rates of improvement within age groups were parallel for computations and retrievals, suggesting a single, age-attenuated mechanism that affects practice-related speedup. The age-related delay in strategy shift suggests either reluctance to use retrieval or an associative memory deficit. Experiment 1 showed that skill acquisition was unaffected by the presence and frequency of postresponse strategy probes for both age groups. Experiment 2 showed that pretraining item-learning operations facilitated subsequent item learning and that pretraining either item-learning operations or the algorithm did not alter the age trends.

Keywords: cognitive skill learning | arithmetic problem solving | strategy shifts | age differences | age deficits | computation speed | retrieval | postresponse strategy probes | pretraining

Article:

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The learning of cognitive skills is fundamental to effective functioning at any age. Compared with younger adults, older adults acquire new skills more slowly and usually do not reach the same asymptotic level of skilled performance as younger adults (e.g., Charness & Campbell, 1988; Dunlosky & Salthouse, 1996; Harrington & Haaland, 1992; Hashtroudi, Chrosniak, & Schwartz, 1991; Hoyer, Cerella, & Onyper, 2003; Jenkins & Hoyer, 2000; Rogers, Hertzog, & Fisk, 2000; Salthouse, 1994; Salthouse & Somberg, 1982; Siegler & Lemaire, 1997; Strayer & Kramer, 1994; Touron & Hertzog, 2004a, 2004b; Touron, Hoyer, & Cerella, 2001). That there is an age-related deficit in skill learning has been known for a long time (Bryan & Harter, 1897; Miles, 1933; Thorndike, Bregman, Tilton, & Woodyard, 1928). In the study by Thorndike et al., for example, pronounced age differences were observed in training right-handed younger and older adults to write left-handed.

Studies have advanced several kinds of explanations for age-related deficits in skill learning, including relatively inefficient learning strategies and response biases on the part of older adults (e.g., Rogers & Gilbert, 1997; Rogers et al., 2000; Strayer & Kramer, 1994; Touron & Hertzog, 2004a, 2004b), age-related deficits in the associative aspects of learning and retrieval for repeated problems (e.g., Hoyer et al., 2003; Jenkins & Hoyer, 2000; Touron et al., 2001), and the pervasive influence of age-related slowing on some or all of the component processes involved (e.g., Brigman & Cherry, 2002; Dunlosky & Salthouse, 1996; Fisk & Warr, 1998; Salthouse, 1994; Verhaeghen & Marcoen, 1994). Empirical work to date has not convincingly demonstrated that just one of these factors is largely responsible for age-related skill-learning deficits. Indeed, current theories of skill acquisition point to both strategy factors, such as qualitative differences and practice-related shifts in how solutions are obtained and practice-related improvements in processing efficiency (e.g., Anderson, 1993; Gupta & Cohen, 2002; Haider & Frensch, 2002; Logan, 1988; Rickard, 1997). It is quite possible that strategy inefficiencies, process-general slowing, and associative deficits all contribute to the extent to which older adults show deficits in skill-acquisition tasks. We offer a precise depiction of age differences in the component processes of skill acquisition, allowing for a clearer consideration of prospective causal mechanisms.

Aging and Strategies in Skill Acquisition

Skilled performance in natural settings is typically memory based, relying on the individual's adoption and adaptive use of recurring instances that comprise the skill domain (e.g., Bosman & Charness, 1996; Ericsson & Charness, 1994; Hoyer & Ingolfsdottir, 2003). Only for relatively novel problems is it necessary to apply the computations or rules that govern the skill domain to the problem at hand. Studies of the acquisition of cognitive skills in the laboratory have uncovered the same dynamics (e.g., Logan, 1988; Rickard, 1997; Schunn, Reder, Nhouyvanisvong, Richards, & Stroffolino, 1997). Early in training, computationally based responding is slow but applies successfully to the entire problem domain; late in training, memory-based responding is fast but is limited to the training set. A shift in the way solutions are obtained, from computationally based responses to memory-based responses, occurs with repetitions (e.g., see Haider & Frensch, 2002; Logan, 19880, 19920; Rickard, 1997, 2004).

We apply the term strategy to refer to the method used for obtaining solutions in skill-learning tasks in which different methods are possible. It is usually, if not always, the case that different strategies can be used in acquiring and executing cognitive skills, and there is now a substantial amount of evidence to indicate that the strategies used by older adults in a variety of learning situations are less optimal than those used by younger adults (e.g., Dunlosky & Hertzog, 2001; Hulicka & Grossman, 1967; Rogers & Gilbert, 1997; Rogers et al., 2000; Touron & Hertzog, 2004a, 2004b). The findings of the studies by Rogers et al. (2000) and Rogers and Gilbert (1997) suggested that age-related differences in skill acquisition are exacerbated by the use of nonoptimal strategies by older adults. For example, Rogers et al. (2000) compared the performance of young and older adults in a task in which participants judge whether a centrally presented target noun pair is matched in a key presenting the full set of consistent noun pairings at the top of the screen. As noun pairs are repeated, responses may be made either by scanning the key or by retrieving the solution from memory. At the end of training, each participant's strategy performance was classified as being primarily based on either scanning or retrieval by means of individual response time (RT) distributions. Rogers et al. (2000) showed that the age groups were not different in terms of absolute performance and ability-performance relations when age group comparisons were made within strategy classifications. In an earlier study using the same noun-pair task and classification system, Rogers and Gilbert (1997) reported that age-related differences in performance (i.e., RT improvements) were attributable to strategy differences in that older adults were less likely to use retrieval as the method for making responses. Rogers and Gilbert also found that use of the more efficient strategy, retrieval, could be increased in older adults by making the benefits of retrieval more conspicuous. The advantage of using retrieval instead of scanning was made salient by presenting noun pairs without the look-up key on some trials. Touron and Hertzog (2004a, 2004b) have reported that there is a greater reluctance on the part of older adults to shift from a scanning strategy to retrieval of noun pairs during the course of skill learning, even when they have sufficient knowledge of the noun-pair associations to do so. In the experiments reported here, we used relatively difficult pseudoarithmetic computation instead of a scanning versus retrieval task because of the built-in incentive to retrieve instead of to perform a calculation. In this task, the demands of computation could provide an even stronger incentive for the old than for the young.

In skill-learning tasks that contain repeated problems, improvements in performance with practice can be tied to at least three types of processing operations: (a) computing efficiency in terms of speed and accuracy; (b) retrieval speed and accuracy; and (c) a repetitions-based shift from computing to retrieving. Computing is required when individuals apply a rule or algorithm to obtain solutions to novel or rare problems. An age-related deficit in the efficiency of computing could contribute to impaired performance. With repeated presentations of the same problem, solutions can be retrieved from memory in lieu of computation. For example, adults presumably possess a knowledge base of numerical facts that enables them to retrieve solutions from memory (e.g., 12 + 12 = 24) instead of having to carry out a counting algorithm. The shift to retrieval and the speed and accuracy of retrieval could also be sources of age-related deficits in skill learning.

One method for directly examining practice-related changes in the components and strategies used in skill learning involves the use of postresponse reports by participants of the strategies used for obtaining solutions (Compton & Logan, 1991; Delaney, Reder, Staszewski, & Ritter, 1998; Rickard, 1997, 2004; Schunn et al., 1997). In one of the first studies using this method, Compton and Logan (1991) had participants make verification responses to repeated alphabet arithmetic equations of the form H + 3 = K; in this case, the answer is true because K is three steps away from H in the alphabet. After one sixth of the trials, participants were instructed to report whether the answer to the problem just presented was obtained by counting or by remembering the answer without counting (as problems were repeated). Compton and Logan provided evidence to suggest that there was a transition from counting to memory-based processing. To assess the validity of the probe procedure, an RT estimation procedure was used to show that the retrieval responses were represented in the same proportions on probed and nonprobed trials. In Rickard (1997), participants were taught to solve pseudoarithmetic problems that contained a novel synthetic operator, #. Participants reported whether they used the taught algorithm to obtain the answer, retrieved the answer directly from memory, or used some other strategy that did not correspond to either computation or retrieval. Strategy probes were administered after the participants' responses on one third of the trials, and responses to the probes allowed for the extraction of separate curves for computes, retrieves, and the shift from algorithm computation to retrieval. Hoyer et al. (2003) further validated the strategy probe methodology by demonstrating that reported computations for an alphabet-arithmetic task increased with addend size, whereas reported retrieval responses did not vary by addend.

Aging, Memory, and Associative Deficits in Skill Acquisition

As mentioned, the prevailing theories of cognitive skill acquisition call attention to improvements associated with task strategies and improvements in the accuracy and speed of carrying out the requisite learning processes (e.g., Anderson, 1993; Gupta & Cohen, 2002; Logan, 1988; Rickard, 1997). It is well known that there are large age-related deficits in the efficiency of many types of learning, including associative learning (e.g., Salthouse, 1994; Salthouse, Kausler, & Saults, 1988; for a comprehensive review, see Kausler, 1994). Further, there are numerous reports of age-related differences in skill-learning tasks, which might be partially attributable to age-related deficits in associative learning (e.g., Hoyer et al., 2003; Jenkins & Hoyer, 2000; Rogers & Gilbert, 1997; Rogers et al., 2000; Touron & Hertzog, 2004a, 2004b; Touron et al., 2001). Jenkins and Hoyer (2000) showed that the number of repetitions needed to reach automaticity in an enumeration task with repeated configurations was greater for older adults than for younger adults. The findings suggested an age-related deficit in associating particular configurations with particular digits and in shifting from a counting strategy to retrieving instances. In the study by Touron et al. (2001), younger adults and older adults were given training with one set of alphabet arithmetic problems and then were given training on a second set of different problems that involved using the same algorithm or memory retrieval. Analyses of the parameters of power function fits by age and problem set revealed age deficits in asymptotes and learning rates for both problem sets. These age deficits were found in the acquisition of both problem sets; in addition, the age difference in the learning rates was larger for Problem Set 2 than for Problem Set 1, suggesting that older adults derived less benefit from practice with rule use or from practice in building associations between problems and their solutions in Set 1 training. Without strategy probes, it was not possible to evaluate separately the effects of practice on item retrieval and computational speedup for younger and older adults or to distinguish the contributions of retrieval and computational speedup in Set 1 to skill learning performance in Set 2.

Comparative Assessment of the Components of Skill Acquisition

We report the results of two experiments in which we examined the effects of practice on strategy shifts and on the speed and accuracy of computing and retrieving solutions to repeated problems. By comparing the components of skill acquisition, we can inform a fundamental debate in the study of cognitive aging: whether age-related cognitive declines are based on a general mechanism that is insidious to many functions or whether declines for different tasks (or task components) are process specific. A considerable amount of evidence indicates that processing speed accounts for a substantial part of the age variance in performance across a wide range of cognitive measures (e.g., for a comprehensive review, see Salthouse, 1996). To our knowledge, no studies have comprehensively evaluated age differences and practice-related improvements for multiple processing components during skill acquisition.

In the two experiments that comprise the current study, on-line strategy probes were used to identify computes and retrieves on individual trials. We examined the effects of age on speedup for responses categorized as computes and retrieves by fitting the data to a power function. RT data in skill-learning studies usually exemplify the "power law of practice" (Newell & Rosenbloom, 1981), and the fits of data sorted by strategy to a power function are particularly impressive (Delaney et al., 1998; Rickard, 1997, 2004). In its simplest two-parameter form, the power law states that latencies (RT) will decline with blocks of training (N) on a power function, RT = aN-b, where the coefficient a determines the starting value at N = 1 and the exponent b determines the rate of decline. Given data from two age groups (RT1 and RT2 conforming to the power law, the extent to which there is a difference in skill learning is reflected in the difference between b1 and b2.

The test for an Age Group × N interaction can be described exactly as a test for the constancy of RT2 − RT1 over N. The constancy of RT2 − RT1 reflects the equality of b1 and b2. Thus, a simple, straightforward approach is to apply a log transform to both RT values and N. In logarithmic units, RT will be a linear function of N. As shown by Newell and Rosenbloom in their original study (1981), if RT = aN-b, then ln(RT) = -$b$ln(N) + ln(a). The slope of the function is equal to the power function exponent, and the intercept is equal to the log of the starting value. Log-transformed values can then be submitted to an analysis of variance (ANOVA)-based trend analysis on N. The strength of the linear component exposed by the analysis serves as an index to the validity of the power function model. Given that the log-log data are largely linear, a significant interaction between condition and the linear component of N can be legitimately interpreted as a difference in slopes between groups or conditions or, equivalently, as a difference in the power function exponent (and conversely for a nonsignificant interaction). In every case, the Group × Linear N interaction term, if statistically reliable, correctly signals a difference in learning rate. Further, in log-log plots, the linearity of the trends (and hence the appropriateness of the power function model) is apparent on visual inspection, as is the relation between two trends (parallel, divergent, or convergent lines).

The use of strategy probes allows for analysis of the proportion of retrieval responses P (or its complement [1 - P], the proportion of computational responses). P can be plotted block by block and has been found to rise from 0 to 1 on a negatively accelerated function of N (e.g., Rickard, 1997). The $P \times N$ trace reflects the progression of the strategy shift across blocks of training. Consistent with Rickard's (1997) neural network simulation of the shift from computation to retrieval, some of the classic work on paired-associate learning points to a negative exponential item-acquisition function (e.g., Atkinson, Bower, & Crothers, 1965). We suggest that the strategy shift rate reflects both the efficiency with which stimulus-response connections are encoded and represented in episodic memory as well as any response bias against using retrieval as a strategy. In light of well-known age-related deficits in associative learning and binding (e.g., Naveh-Benjamin, 2000), as well as a possible disinclination to use retrieval as a strategy (see Touron & Hertzog, 2004a, 2004b), it is likely that the probability of retrieval across blocks of training is an age-sensitive component in skill learning.

The effects of training on P in two groups ($P1$ and $P2$) are assessed by examining the Group $\times N$ interaction term. This test will be direct if the $P1 \times N$ and $P2 \times N$ traces are linearized. If the growth in P is negative exponential, $P = 1 - e^{-c(N-1)}$, a straightforward transformation is applicable, and that is to first form the complement of P, $Q = 1 - P$, and then to do a log transform of the Q values. (N values are not transformed; this is described as a semilog rather than as a log-log transform.) In semilog units, Q will be a linear function of N, whose slope is equal to the exponential rate parameter. Mathematically, if $P = 1 - \exp(-c(N - 1))$, then $Q = \exp(-c(N - 1))$ and $\ln(Q) = -c(N - 1)$. If a trend analysis is performed on the semilog values, we are justified in interpreting an interaction between condition and the linear component of N, as a difference in the learning rate. Also, from semilog plots, the linearity of the trends (and hence the appropriateness of the negative exponential model) is apparent on inspection, as is the relation between two trends (collinear or divergent lines).

To summarize our treatment of the data in the current experiments, three steps were involved. First, strategy probes were used to decompose performance into three components of skill—computation times, retrieval times, and proportions of retrievals—all as a function of block. Second, the indicated transformations were applied to the component data, a log-log transform in the case of the latencies and a semilog transform in the case of the proportions. Linear trends in the resulting traces captured the learning rate for each component. Third, rate differences between conditions or age groups were assessed visually in terms of parallel, divergent, or convergent trends and confirmed statistically by means of ANOVA-based trend analysis.

Experiment 1

One of the aims of this experiment is to provide a relatively precise description of practice-related speedup in computed and retrieved responses and the shift from computation to retrieval in younger and older adults. To our knowledge, age effects in these particular components of skill learning have been assessed in only three studies: one that examines age and item difficulty effects in an alphabet arithmetic task (Hoyer et al., 2003) and two that examine age and strategy choice effects in the noun-pair task (Touron & Hertzog, 2004a, 2004b). Although these previous studies primarily examined strategy information to compare rates of strategy shift across groups, the current research offers a detailed depiction of improvements within each of the component processes as well as a more precise analytic approach for comparing strategy shifts.

Because of the multistep nature of the selected computation, RTs were expected to be substantially shorter for retrieves than for computes. Consistent with Rickard (1997, 2004), it was predicted that RTs for both computes and retrieves would become shorter with repetitions. In terms of age effects, we expected that the strategy shift from computation to retrieval would require more repetitions for older adults than for younger adults. An age-related reduction in the shift rate from computes to retrieves could be interpreted to reflect a true age-related deficit in the ability to learn and retrieve associations between problems and their solutions, or it could reflect a disinclination on the part of older adults to use retrieval as a strategy for obtaining solutions. Improvement rates for both computational and retrieval times were expected to be slower for older adults than for younger adults. Of most importance are the relations between age and the exponents of the trends for computes and retrieves. Findings showing that there are age differences in the log-linearized trends for both computes and retrieves, and that the trends are parallel for computes and retrieves within age groups, could be taken as strong evidence for a general learning mechanism that is age attenuated. Findings of different trends for computes and retrieves either within or between age groups suggest the need for a process-specific interpretation of computational learning and retrieval learning and the associated age effects.

A second purpose of this experiment was to examine whether skill acquisition is reactive to the administration of probes and the frequency of probing. The examination of possible age differences in the extent to which probing affects processing efficiency and strategy use is essential to determining the value of postresponse strategy probes as a method for decomposing the strategies involved in skill learning. As mentioned, Rogers and Gilbert (1997) showed that interim tests served to increase older adults' use of retrieval as a strategy for obtaining solutions in a noun-pair learning task. Like the effects of interim tests or the effects of other task manipulations designed to boost retrieval use (e.g., presentation of trials without the look-up key), it is an open question whether the administration of postresponse strategy probes affects measures of response accuracy, speedup for computes and retrieves, or the probability of retrieves in either younger or older adults. Further, it must be established that the probe procedure used for identifying responses as computes and retrieves accurately reflects the speedup patterns observed during the course of acquisition.

Rickard (2004) reported that strategy probes produced faster rates of item learning in younger adults. However, this outcome might have been confounded by the inclusion of an unrelated secondary task in the place of the strategy probe for the nonprobed group (judgment of spatial locations for geometric shapes). Switching from the primary pound-arithmetic task to an unrelated secondary task might have induced a task-switching effect, disrupting primary-task performance in the nonprobed group. We did not include a secondary task in our procedure, the more so because any interference or task-switching demand would likely be greater for older adults than for younger adults (e.g., Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). Our experiment was designed to expose possible differences in skill acquisition with 33% probing, 100% probing, and no probes. We hoped to establish that skill acquisition assessed in the presence of strategy probes at either frequency was no different than that assessed without probes for either younger or older adults.

In the current experiment, younger adults and older adults were taught to solve pseudoarithmetic equations that contained a novel operator (#) and were subsequently assessed on a skill-acquisition task consisting of repeated problems containing this operator. The task, referred to as pound arithmetic, was used previously by Rickard (1997) to examine the repetition-based shift from computation to retrieval in young adults. Problems having the form $A \# B = C$, were presented on each trial. A, B, and C were two-digit numbers conforming to the operation $[(B - A) + 1] + B = C$. For different groups of participants, strategy probes either were administered on 33% of the correct trials or 100% of the correct trials or were not given. These frequencies were chosen to contrast outcomes from nonprobed responses and 100% probed responses to Rickard's (1997) reliance on probes for 33% of trials. For the 33% and 100% groups, the proportions of item retrievals were examined as a function of the number of repetitions, and response times for computes and retrieves were examined separately as a function of repetitions based on the strategy reports.

METHOD

Participants

The participants were 48 younger adults aged 18 to 25 years and 48 older adults aged 60 to 75 years. Within each age group, 16 participants were assigned to each of the three probe conditions (0%, 33%, 100%). Younger adults were recruited from the pool of the Department of Psychology at Syracuse University. Older adults were community-residing volunteers recruited from the registry of the Adult Cognition Laboratory at Syracuse University and received an honorarium ($10–15/hr) for their participation.

Before testing, participants reported their education level and medication usage and used a 5-point scale to rate their overall physical health, illness-related physical limitations, and degree of comfort with using a computer. Individuals who reported that they were not taking any medications known to affect memory or learning and who rated their health, physical activity level, and comfort level with computers as good or excellent (ratings of 2 or 1, respectively) were eligible to participate in the experiment. Also, participants were screened for near-visual acuity and were excluded from participation if acuity was worse than 20/30 (corrected).

The Digit Span and Digit Symbol Substitution subtests of the Wechsler Adult Intelligence Scale-Revised (Wechsler, 1981) were administered for the purpose of describing the age samples. Mean scores and standard deviations for these measures are reported in Table 1.

Materials and procedures

The participants' task was to make true and false responses to equations that contained a novel arithmetic operator (#). Problems had the form $A \# B = C$, where A, B, and C were two-digit numbers. Problems were true if they conformed to the equation $[(B - A) + 1] + B = C$ and were false if they did not conform this equation. The experimenter explained the operations for solving the problems, and participants practiced solving problems before testing. Computer testing began after the participant correctly solved 8 problems with paper and pencil and 3 problems without paper and pencil. Computer testing involved a set of 10 problems, 5 true and 5 false. Each participant was randomly assigned to 1 of 2 problem sets (see the Appendix). To eliminate the possibility of participants' learning true-false associations to particular values of *C* rather than to whole equations, the 5 true equations used different values of *C*, and false equations were constructed using the same 5 values. Problems were presented horizontally in the center of a computer screen at eye level. Problems subtended approximately 6 degrees of visual angle at a viewing distance of 50 cm. Stimulus presentation and the recording of response times were controlled by programs in Visual Basic 6.

Table 1
Means and Standard Deviations for Measures of the Characteristics of the Research Participants in Experiment 1

	Young adults		Older adults	
Measure	*M*	*SD*	*M*	*SD*
Age (years)*	20.08	2.40	68.96	4.30
Education*	13.75	1.60	15.00	2.30
Health	1.90	0.70	1.90	0.70
Limitations	1.30	0.70	1.60	0.90
Digit Span	15.28	3.50	16.46	3.60
Digit Symbol*	71.42	11.70	55.68	10.00

Note. Each age group contained 48 men and women. Education = self-reported number of years of formal education. Health = self-reported using a scale from 1 (*excellent*) to 5 (*poor*). Limitations = self-reported number of health-related limitations. Digit Span = measure combines the forward span and backward span scores for the Wechsler Adult Intelligence Scale—Revised (WAIS–R) Digit Span (Wechsler, 1981). Digit Symbol = score on WAIS–R Digit Symbol Substitution subtest.
* $p < .01$.

Participants were tested in a single session consisting of 25 blocks, which lasted approximately 1.5 hr. Each block contained 30 trials, three repetitions of each of the 10 items. Thus, each equation was presented 75 times. Participants responded by pressing keys marked *true* and *false.* Order of presentation of the items was random within each block. Rest breaks were offered after completing each block. Each trial consisted of the presentation of a fixation cross for 500 ms followed by the presentation of one of the equations. The equation remained on the screen until a keypress was made. For 0%, a random 33% of the correct trials, or 100% of the correct trials, a strategy probe was presented immediately after a true-false keypress. The strategy probe instructed the participant to report whether the response that was just made was the result of computation or memory retrieval of the solution or otherwise. Three keys on the computer keyboard were labeled *C*, *M*, and *O* for the participant to respond either “compute,” “memory,” or “other” to the probe. On-screen instructions for the strategy probes were as follows: “If you computed the solution, press *C*. If you remembered the solution, press *M*. If other, press *O*.” For correct responses, a blank screen for 500 ms followed each strategy response. For incorrect responses, the equation was re-presented for 2,000 ms followed by a blank screen for 500 ms.

RESULTS

The dependent measures of interest were overall RTs and RTs sorted by strategy probes across training, accuracy of responses across training, and retrieval proportions across training. Response times longer than 80,000 ms or shorter than 300 ms were considered outliers, resulting in the removal of less than 0.01% of responses. Mean correct RTs were calculated for each participant for each block of repetitions and were aggregated within age and condition groups.

As described, log-log (latencies) or semilog (proportions) transformations were applied to express the data as linear trends. The effects of repetitions on retrieval proportions derived from the participants' strategy reports are shown in Figure 1, and the effects of repetitions on RTs are shown in Figures 2 and 3. In all figures, antilog markers are provided to assist interpretation. A repeated measures ANOVA was used to test for the effects of age (young, old), strategies (computation, retrieval), probe conditions (RTs: 0%, 33%, 100%; probability of retrievals; 33%, 100%), and repetitions (1–60).

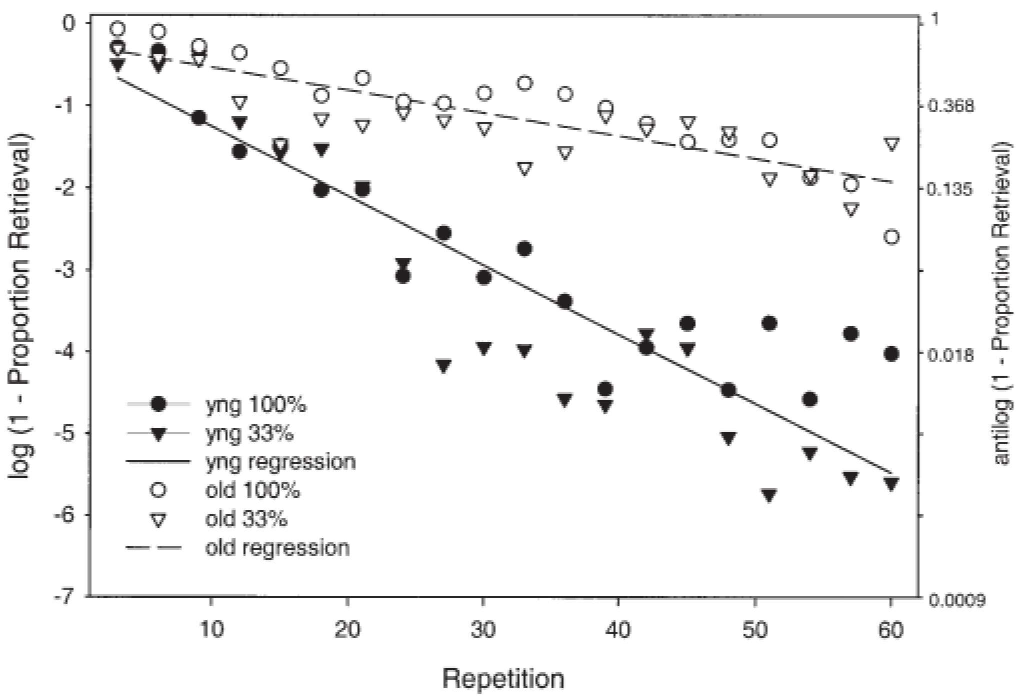

Figure 1. Proportions of item retrievals by age and probe frequency as a function of repetitions in Experiment 1. yng = young.

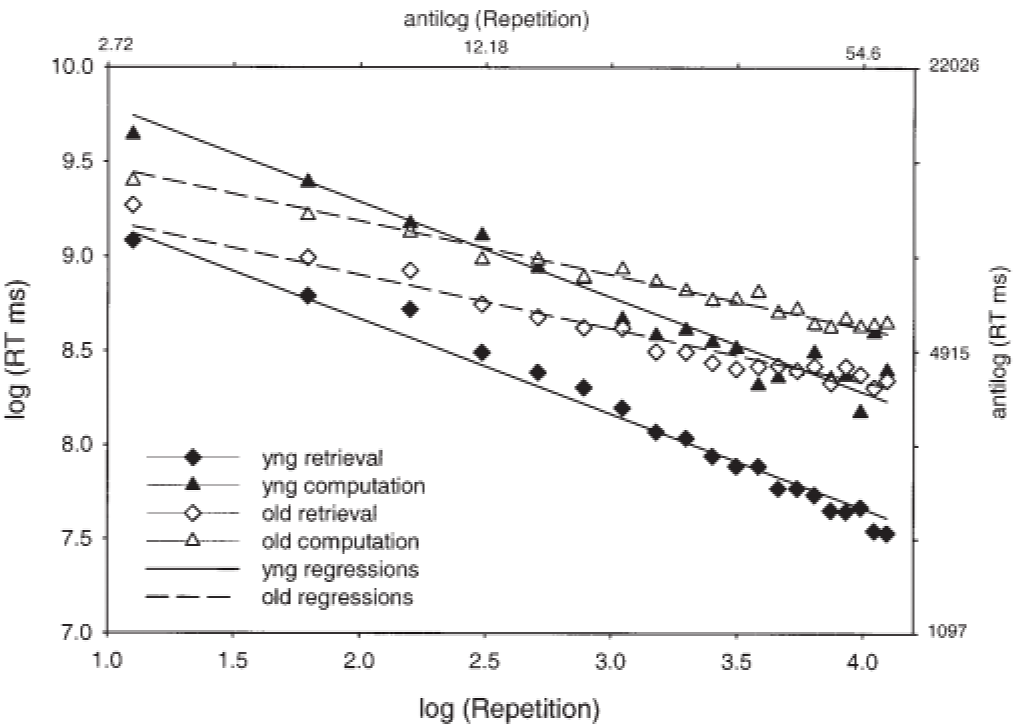

Figure 2. Mean response times (RT) by age and strategy (computes, retrieves) as a function of repetitions in Experiment 1. yng = young.

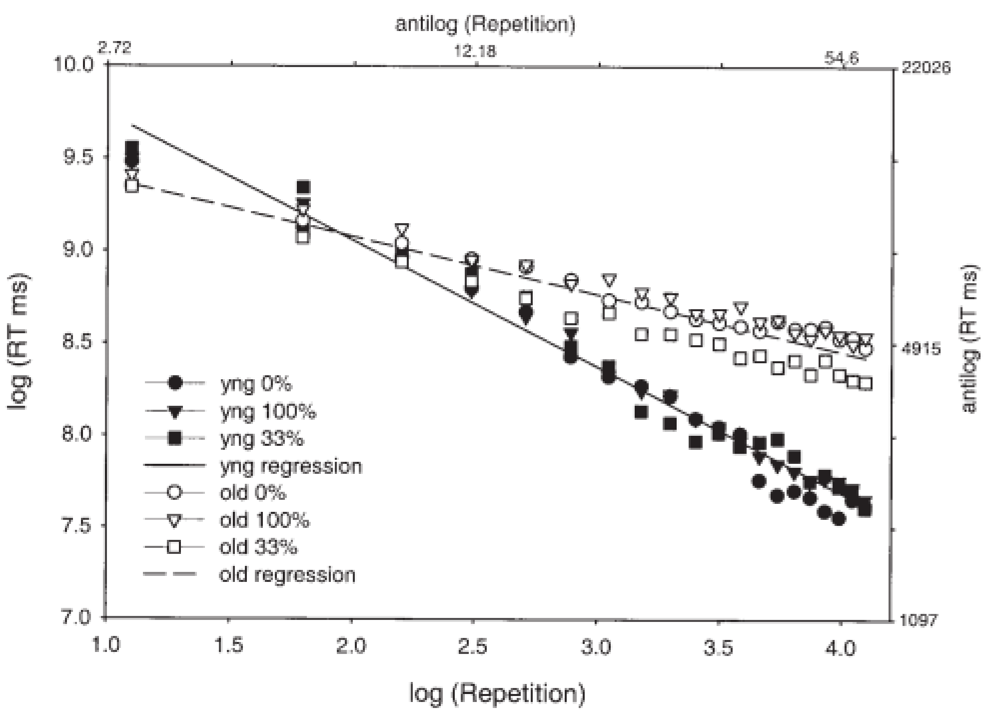

Figure 3. Mean response times (RT) by age and probe frequency as a function of repetitions in Experiment 1. yng = young.

Retrieval proportions

Item learning is expressed as a decline in strategies for solutions other than the strategy of direct retrieval of the problem and its solution from memory. Nonretrieval strategies included reports of "compute" and "other." "Other" responses to the strategy probes were very rare (>2%). Item learning is shown as log (1 − proportion retrievals) as a function of repetitions in Figure 1. Analyses are based only on the 33% and 100% probe conditions because strategy information was unavailable for the participants in the 0% probe condition. Retrieval proportions increased as a function of linear repetitions, $F(1, 53) = 100.94$, $p < .01$. The linear effect accounted for 97% of the variance, and none of the higher order effects was significant. Older adults reported substantially less overall retrieval use, $F(1, 53) = 24.92$, $p < .01$, and the rate of increase in retrieval use as a function of linear repetitions was less for older adults than for younger adults, $F(1, 53) = 25.81$, $p < .01$, for the Age × Linear Repetitions interaction. There was no effect of the frequency of strategy probes on the course of skill acquisition. The proportions of retrievals were unaffected by probe frequency, as indicated by the absence of main and interaction effects (frequency: $p = .33$; Age × Frequency: $p = .72$; Linear Repetition × Frequency: $p = .44$; triple interaction: $p = .07$).

RTs by strategies

Analyses are again based only on the 33% and 100% probe conditions because strategy information was unavailable for the participants in the 0% probe condition. As can be seen in Figure 2, mean RTs by strategies (computes and retrieves) for younger and older adults are largely linear as a function of repetitions in log-log coordinates, $F(1, 59) = 116.36$, $p < .01$. The linear effects accounted for 82% of the variance resulting from repetitions. The quadratic and triadic effects of repetitions on RTs by strategies contributed an additional 16% and 2% of the variance in repetitions beyond the linear trends, respectively. Thus, speedup in RTs sorted by strategies was largely albeit not entirely power functional.

The data shown in Figure 2 suggest that the rate of repetitions-based improvement was slower overall for older adults than for younger adults, that rates of improvement in RTs were roughly the same for algorithmic computation and retrieval, and that the rates of improvement for computation and item learning were largely parallel within age groups. These observations were confirmed by statistical analysis. The Age × Linear Repetitions interaction, favoring young adults, was significant, $F(1, 59) = 5.88$, $p < .01$. As expected, RTs were longer for computations than for item retrievals, $F(1, 59) = 10.38$, $p < .01$. The Strategies × Linear Repetitions interaction ($p = .13$) and the Age × Strategies × Linear Repetitions interaction ($p = .68$) were not significant. RTS were longer for older adults than for younger adults, $F(1, 59) = 7.35$, $p < .01$.

Overall RTs

As can be seen in Figure 3, the log-log trend for overall RTs by age and probe frequency was largely linear, $F(1, 82) = 552.91$, $p < .01$. The linear term carried 89% of the variance resulting from repetitions. Beyond the linear trend, the quadratic and triadic trends accounted for an additional 10% and 1% of the variance, respectively.

The analysis of overall RTs by age and probe frequency revealed two findings. First, rate of improvement in overall RTs was slower for older adults than for younger adults, as indicated by the Age × Linear Repetitions interaction, $F(1, 82) = 85.33$, $p < .01$. RTs, overall, were significantly longer for older adults than for younger adults, $F(1, 82) = 55.01$, $p < .01$. Second, there was no effect of the presence or the frequency of strategy probing on rate of improvement. Overall RTs were comparable between probe frequency groups (frequency: $p = .57$; Age × Frequency: $p = .40$), and probe frequency did not influence the linear repetition effect ($p = .93$) or the Age × Linear Repetitions interaction ($p = .84$).

Accuracies

Mean response accuracies by age and condition are shown in Table 2. Mean accuracy was 93.4% for the older adults and 90.1% for the young adults, and this difference was significant, $F(1, 82) = 7.06$, $p = .01$. Accuracy of skill acquisition responses improved with repetitions, $F(19, 1558) = 2.15$, $p < .01$, and there were no interactions involving repetitions (all ps $> .6$). There were no significant effects of probe frequency ($p = .4$) or interactions with probe frequency ($p = .7$).

Table 2

Means and Standard Errors of Percentage of Response Accuracy for Experiments 1 and 2

	Young adults		Older adults	
Condition	*M*	*SE*	*M*	*SE*
Experiment 1				
0% probing	91.9	1.5	94.5	1.6
33% probing	90.7	1.5	91.8	1.5
100% probing	89.4	1.5	94.4	1.5
Experiment 2				
Item pretraining	90.9	2.1	88.5	2.2
Rule pretraining	88.7	2.1	90.1	2.1
Control	91.4	2.2	91.4	2.1

DISCUSSION

The findings of this experiment serve to establish firmly that strategy probes are useful for assessing component strategies and the shift from computation to item retrieval in repetition-based cognitive skill acquisition. Throughout the 600 trials of skill learning, RTs were invariably and reliably longer for reported computations than for reported retrievals (also see Hoyer et al., 2003; Touron & Hertzog, 2004a, 2004b). Our findings also suggest that the presence and frequency of strategy probes did not noticeably affect the amount of learning for younger and older adults. RTs, the probability of retrievals, and the rates of speedup for computations and item retrievals were unaffected by manipulations of the frequency of strategy probes. However, some caution is in order; the three-way interaction between age, probe frequency, and repetitions for retrieval proportions approached statistical significance ($p < .07$). Decomposition of this interaction suggested that probe frequency may have had an effect on the performance of the young adult participants in that the performance of this group was somewhat reduced in the 100% probe condition compared with the 33% probe condition. In addition, the effect of probing on the performance of the older adults may have been negligible because of attenuated item learning by older adults in every condition.

In contrast to Rickard's (2004) finding with younger adults that skill acquisition was faster with strategy probes than without strategy probes, we found no evidence to suggest probe reactivity effects on rate of acquisition (and a marginal detriment for frequent probing). Rickard's inclusion of a filler task in the place of strategy probes in the nonprobed condition could have served to impair skill learning, resulting in relatively better performance for the probed group. On the basis of the results of studies of the relations between age and dual-task conditions (e.g., Verhaeghen et al., 2003), we suspect that the inclusion of a filler task in their experiment would have given a distorted picture of probe frequency effects and of the magnitude of age-related impairments in the skill-learning performance.

This experiment extends the methods and findings of a small number of studies in which proportions of item retrievals by repetitions are measured and RTs for computes and retrieves are separately analyzed across repetitions (Compton & Logan, 1991; Rickard, 1997). In those studies and in a few others in which computes and retrieves were dichotomized on the basis of response durations (e.g., Haider & Frensch, 2002), improvements in performance with repetitions have been shown to depend on one or several of the following operations: a shift from computation to item learning by acquiring associations between problems and their solutions; speedup in carrying out the prescribed algorithm perhaps by the compiling or chunking of steps; and speedup in item retrieval responses.

Our experiment provides a highly resolved description of age effects in cognitive skill acquisition at the level of component operations. Given the linear characterization of item learning after log or semilog transformations of the data (the log-linear effects accounted for 82% of the variance associated with repetitions for strategy-specific RTs and 89% of the variance for overall RTs; the relation between semilog retrieval proportions and repetitions was overwhelmingly linear, accounting for 97% of the effect of repetitions on retrieval reports), the effects of age and of other variables on rates of improvement were disclosed by the extent to which these variables interacted with linear repetitions.

A key finding was the demonstration of an age deficit in the shift rate from computation to retrieval. This rate reduction could be attributable to strategy bias (in favor of computational solutions) or to an age-related inefficiency in building and remembering associations between a particular problem and its solution. A second finding was the parallel rates of speedup in computation times and retrieval times within each age group. The parallelism suggests that a single mechanism may underlie the speedup in computations and retrievals observed in Figure 2 and that this mechanism is age sensitive. The implications of this finding for skill-acquisition theories will be taken up after presentation of Experiment 2. In that experiment, we further examine age effects in retrieval proportions and in the rates of computation and item retrieval by pretraining the operations of item learning and the operations involved in using the algorithm (rule pretraining).

Experiment 2

This experiment had two aims. The first was to replicate or extend the findings of Experiment 1 by using a production task rather than a verification task. Considering that there have been reports that different processing steps and different memory processes are involved in arithmetic production and verification (Campbell & Tarling, 1996; Touron et al., 2001), it would be useful to affirm the findings of the first experiment by using a skill-learning task with somewhat different processing characteristics. The second aim was to examine the effects of two types of pretraining on the shift from computation to retrieval and on the course of speedup for computation and retrieval in younger adults and older adults. The rationale for these forms of pretraining follows from assumptions regarding how repetitions-based skill acquisition develops (Logan, 1988; Rickard, 1997); improvement in skill learning is thought to depend on speedup in computation of the algorithm, retrieval in lieu of computation, and speedup of retrieval responses with practice.

Repetitions-based cognitive skill acquisition was assessed after pretraining in one of three conditions: item pretraining, rule pretraining, or control. Participants in the item pretraining condition were given practice in learning correct responses to repeated problems of the form, *A* # *B* = ??, by associating problems and correct responses by trial and error through the use of feedback. Separate item sets were used in the pretraining and main skill-acquisition phases. This form of pretraining is a form of paired-associate learning. It was selected for pretraining because item learning in the course of skill training also involves mapping or developing an association between the problem stimulus and its response. Participants in the rule pretraining condition were instructed in the use of the # operator and were given practice in using the prescribed algorithm to produce solutions to nonrepeated problems of the form, *A* # *B* = ??, by pressing number keys corresponding to the correct answer. The rationale for this condition was to assess how fluency in the algorithm might alter subsequent acquisition of a set of repeated (no longer novel) problems. Participants assigned to a control condition were given practice in responding to problems of the form ?? # ?? = *C* by entering the two-digit number given for *C*, where *C* was any random number between 33 and 99.

To equate the amount of practice given for the three pretraining conditions, a yoking procedure was used. Each participant in the item pretraining condition was taken to an item-learning criterion of five consecutive blocks with greater than 92% accuracy (fewer than two errors for 12 problems). Within age groups, 1 of the participants assigned to the rule pretraining condition and 1 assigned to the control condition were given the same number of training trials as 1 of the participants in the item pretraining condition.

The pretraining manipulation has implications for both Logan's (1988) and Rickard's (1997) theories of skill acquisition. Specifically, Logan's theory sees a retrieval solution as the outcome of a race between competing strategies and predicts that retrievals will be more likely to win against longer computation times. Thus, retrieval solutions should be depressed for participants receiving rule pretraining. Rickard's theory of skill learning involves separate strategy nodes for computation and retrieval. In Rickard's framework, rule pretraining should serve to strengthen the node for computation, and item pretraining should serve to strengthen the node for retrieval. Thus, participants in the item pretraining group should show relatively faster item learning than either of the other groups. For a similar reason, participants in the rule pretraining group should show delayed item learning relative to the other groups because the node for computation has acquired relatively more strength.

Data reported by Haider and Frensch (2002) suggest that there might be some benefit of item pretraining on subsequent item learning. In the Haider and Frensch study, 39 young adults were given repetitions of 18 alphabet arithmetic problems until reaching a learning criterion and were then given repetitions of 18 new problems. Strategy probes were not used, but the investigators identified 19 participants who switched from computation to item learning and 20 who did not switch to item learning on the basis of response latencies. To the extent that it is legitimate to consider these two self-sorted groups as representative of item training and rule training, a much higher level of item learning for the second set of items was exhibited by the item-trained participants (see Figure 4 in Haider & Frensch, 2002). Further, in the study by Touron et al. (2001) discussed earlier, the larger age difference in the item-learning rate for Problem Set 2 can be interpreted to suggest that younger adults derived more benefit from item pretraining and rule pretraining than older adults.

Experiment 2 examined the effects of age on the following measures: (a) the number of repetitions to reach criterion and RTs in the item pretraining condition; (b) proportions of item retrievals by age and pretraining conditions during skill acquisition; and (c) rates of learning reflected in RTs for computation and retrieval during skill acquisition as a function of pretraining conditions.

METHOD

Participants

The participants were 30 younger adults aged 18 to 25 years and 30 older adults aged 60 to 75 years. Methods of participant recruitment and screening were the same as in Experiment 1. Mean scores for descriptive measures and for the demographic characteristics of the participants are summarized in Table 3.

Materials and procedures

Stimuli were pound-arithmetic problems using the same algorithm as in Experiment 1. Unlike Experiment 1, in which participants were instructed to verify equations, participants in Experiment 2 were instructed to produce solutions by making keypresses on the number pad. Stimuli had the form *A* # *B* = ??, where *A* and *B* were two-digit numbers and participants were instructed to enter a two-digit solution.

Trials consisting of the presentation of digit pairs only were interspersed throughout skill acquisition to assess the speed and accuracy of keypressing. As reported in Table 3, keypress RTs were longer for older adults than for younger adults across training. Mean accuracy for entering keypress responses was 0.98, and accuracy was unaffected by age and practice.

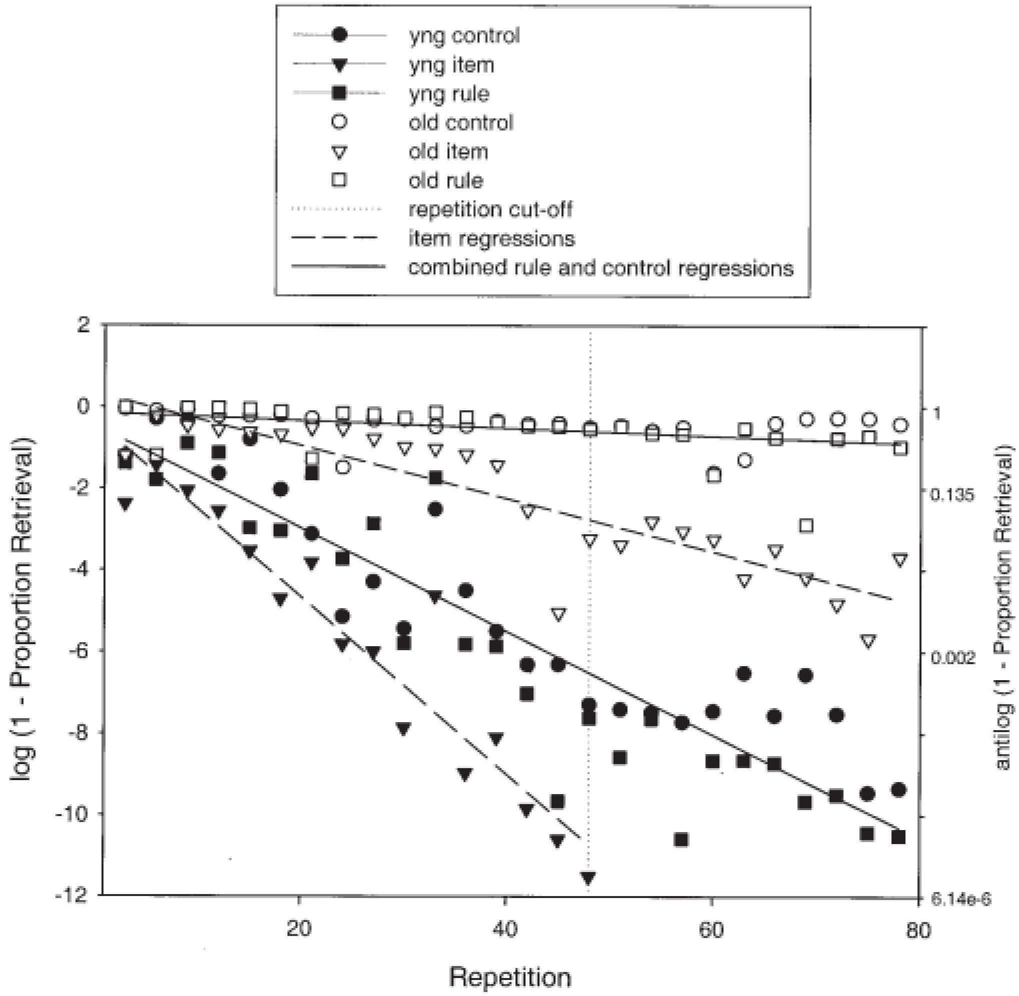

Figure 4. Experiment 2 training, mean log (1 – proportion retrieval) across repetitions by age and type of pretraining (item, rule, control). Linear regressions demonstrate significant main and interaction effects. yng = young.

Testing was conducted individually over four sessions administered on consecutive days. Sessions lasted approximately 1 hr. Ten participants from each age group were assigned to each of the three pretraining conditions. In the item pretraining condition, participants were required to enter responses to equations of the form, *A* # *B* = ??. Each of the eight equations was presented once in consecutive blocks of eight trials. Participants were given no information about the # operator and were forced to learn the correct response by means of solution feedback provided by the computer after an error. In the rule pretraining condition, participants were thoroughly instructed in the use of the # operator and computed and entered solutions for nonrepeated problems of the form, *A* # *B* = ??. Participants in the control condition responded to equations of the form ?? # ?? = *C* by entering the two-digit number given for *C*, where *C* was a random number between 33 and 99.

Table 3
Means and Standard Deviations for Measures of the Characteristics of the Research Participants in Experiment 2

Measure	Young adults		Older adults	
	M	*SD*	*M*	*SD*
Age (years)*	19.37	2.0	69.10	3.6
Education*	12.97	0.9	15.1	2.5
Health	1.6	0.5	1.7	0.7
Limitations	1.2	0.6	1.2	0.7
Digit Span	17.63	3.5	16.43	3.4
Digit Symbol*	70.70	10.7	53.13	8.7
Working memory span*	4.85	0.3	4.13	0.4
Number calculation*	19.7	6.4	29.0	8.7
Number entry speed*	1,060	224	1,392	338

Note. The age groups consisted of 30 men and women. Education = self-reported number of years of formal education; health = self-reported using a scale from 1 (*excellent*) to 5 (*poor*); limitations = self-reported number of health-related limitations; Digit Span = measure that combined the forward span and backward span scores for the Wechsler Adult Intelligence Scale—Revised (WAIS–R) Digit Span; Digit Symbol = score on WAIS–R Digit Symbol Substitution subtest; working memory = span of recall of names of items reordered in terms of size (Cherry & Park, 1993); Number calculation = score on the number subtest of the Primary Abilities Test (Thurstone & Thurstone, 1949); number entry speed = time to make the first keypress in typing a two-digit number appearing on the computer screen, based on 92 trials interspersed among training trials.
* $p < .01$.

In Session 1, participants in the item pretraining condition were trained until they reached a criterion of fewer than two errors in each of five consecutive blocks. At the beginning of Session 2, participants in the item pretraining condition were required to reattain the criterion. Participants assigned to the rule pretraining and control conditions were yoked to participants in the item pretraining condition within age groups to equate the amount of pretraining given across the three conditions. Strategy probes were not given during pretraining. After readministration of the pretraining conditions at the beginning of Session 2, all participants were given instructions for responding to the strategy probes, and participants in the item pretraining and control conditions were given the instructions for using the # operator.

In Sessions 2 to 4, participants responded to 78 repetitions of each of eight problems. A strategy probe followed each response. The procedures for displaying the problems and strategy probes were the same as in Experiment 1. There were 312 experimental trials (26 blocks of 12 trials) per session in Sessions 2 to 4, for a total of 936 experimental trials. Each participant was randomly assigned to one of three problem sets (see the Appendix).

Each of the four sessions began with 120 trials (10 blocks of 12 trials) of number-entry practice. For each number-entry trial, participants keyed in a two-digit number between 33 and 99 that was presented on the computer screen at center fixation. Number-entry trials were also interspersed among the training trials and skill-acquisition trials, such that each block of 12 trials contained 8 problem-solution trials and 4 number-entry trials. Rest breaks were offered after each block.

RESULTS

Participants made responses by entering a two-digit number. The analyses presented later used the latency of the first keypress for correct responses as the dependent measure. RTs longer than 80,000 ms or shorter than 300 ms were considered outliers, resulting in the removal of less than 0.01% of responses. Mean correct RTs were calculated for each participant for each block of repetitions and were aggregated by age and condition groups. The results are shown in Figures 4, 5, 6, and 7 in semilog or log-log coordinates.

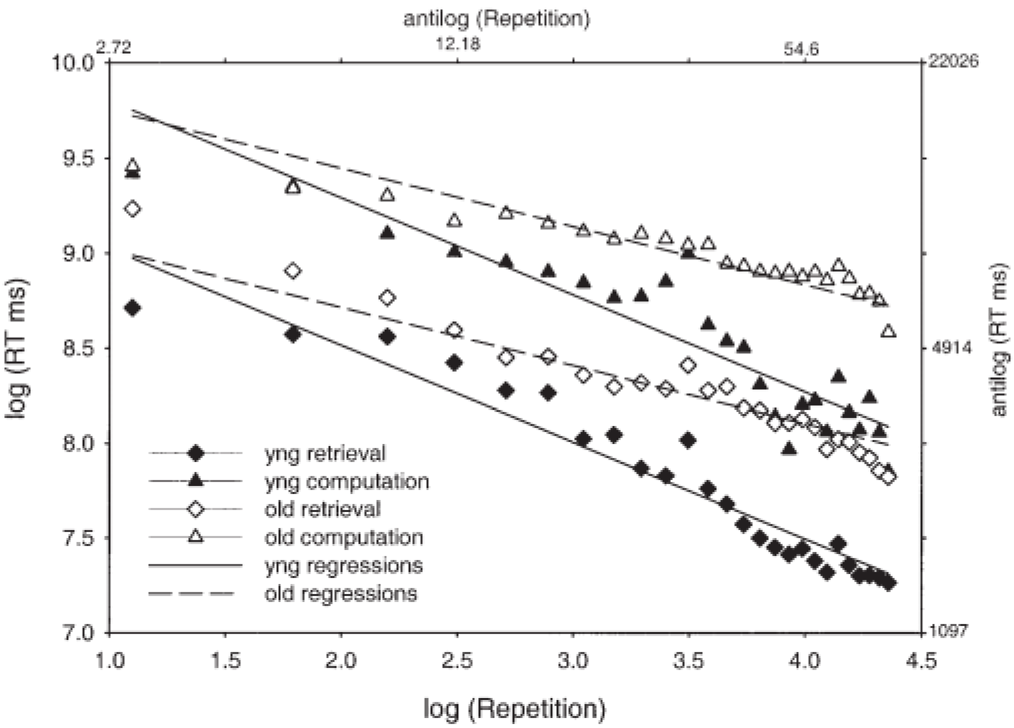

Figure 5. Mean response times (RT) for skill acquisition in Experiment 2 by age and strategy (computation and retrieval) as a function of repetitions. yng = young.

Pretraining

Age differences in the relative effectiveness of the three pretraining conditions were assessed using (a) the number of blocks to criterion for the item-learning condition and (b) criterion response latencies for the item-learning and rule-learning conditions. Analysis of the Session 1 data revealed that older adults required more blocks to reach the criterion than younger adults, $t(18) = -4.04$, $p < .01$ ($M_{old} = 45.9$, $M_{young} = 33.1$). The number of blocks required to reattain criterion in Session 2 was not different for the two age groups, $t(18) = 0.520$, $p > .60$.

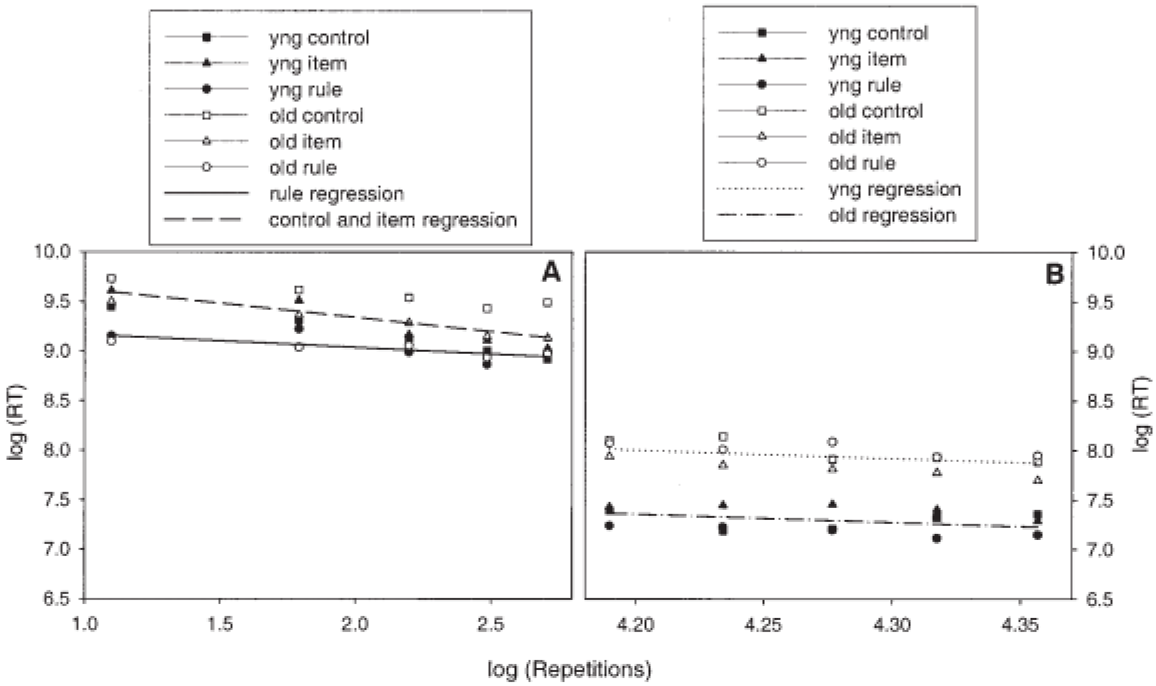

Figure 6. Experiment 2 training; mean log response times (RT) across log repetitions by age, type of pretraining (item, rule, control), and strategy. A: presents computation responses early in training; B: presents retrieval responses late in training. yng = young.

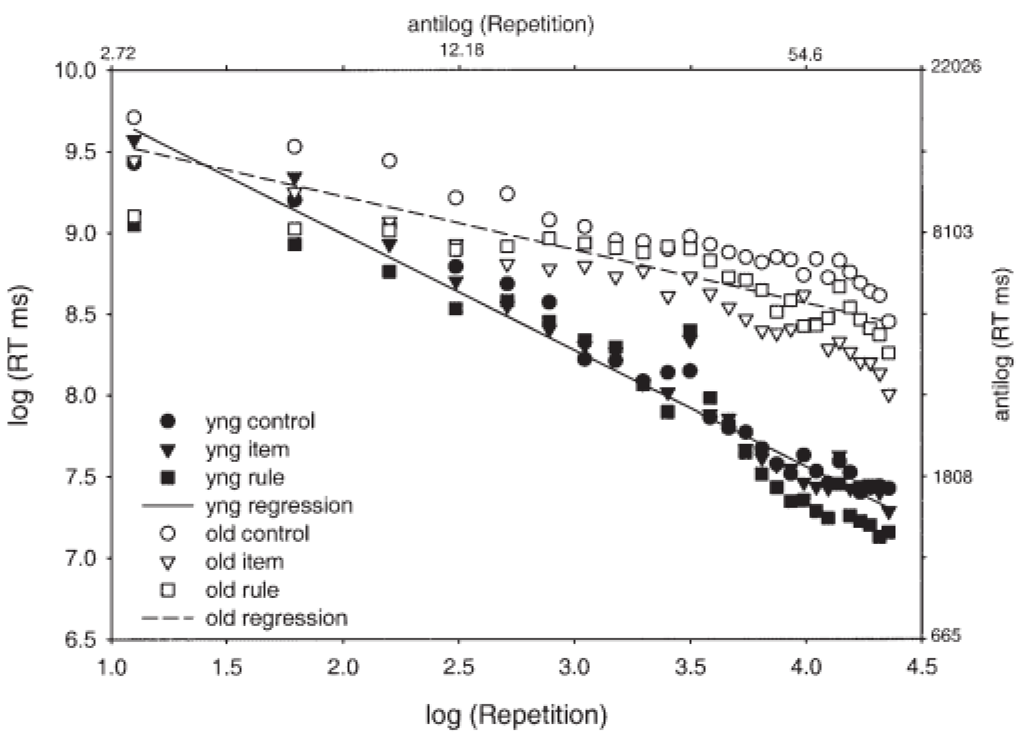

Figure 7. Mean response times (RT) for skill acquisition in Experiment 2 by age and pretraining condition (rule, item, control) as a function of repetitions. yng = young.

RTs for the item pretraining and rule pretraining were compared at criterion across age groups and sessions. Item-learning RTs were not different for younger adults (M = 2,309, SD = 1,472) and older adults (M = 3,123, SD = 1,439), $F(1, 39) = 3.18$, $p > .08$. Further, the difference between RTs for the criterion blocks in Session 1 and Session 2 was not significant, $F(1, 39) = 0.59$, $p > .45$, and the interaction between age and session on the measure of reaching criterion was not significant, $F(1, 39) = 0.67$, $p > .42$. RTs for rule pretraining also did not differ by age (young: M = 8,087, SD = 3,974; old: M = 9,690, SD = 4,644), $F(1, 39) = 1.32$, $p > .26$. Again, the difference between RTs for the criterion blocks in Sessions 1 and 2 was not significant, $F(1, 39) = 2.37$, $p > .13$, and the interaction between age and session on the measure of reaching criterion was not significant, $F(1, 39) = 0.25$, $p > .62$.

Training: Retrieval proportions

Figure 4 shows the proportions of retrievals (or its complement) by groups and repetitions in semilog units. Only Repetitions 1 to 48 were included for analysis. After Repetition 48, many participants reported 100% retrieval, a quantity that is undefined for log (1 - P). Retrieval proportions increased as a function of repetitions, $F(1, 54) = 84.59$, $p < .01$. The linear trend accounted for 87% of the variance in repetitions, and the quadratic trend accounted for an additional 4%. Consistent with the findings of Experiment 1, older adults produced fewer retrievals overall, $F(1, 54) = 66.10$, $p < .01$, and showed a slower rate of increase in producing item retrievals (Age × Linear Repetitions interaction), $F(1, 54) = 48.94$, $p < .01$. Overall, the proportions of retrievals were different for the pretraining groups, $F(2, 54) = 4.76$, $p = .01$. The pretraining group differences in rates of retrievals approached significance, $F(2, 54) = 2.99$, $p = .06$. A series of pairwise comparisons revealed that the rate of item retrieval was greater for participants in the item pretraining condition than for those in the control condition, $F(1, 54) = 4.81$, $p = .03$, and the rule pretraining condition, $F(1, 54) = 4.12$, $p < .05$. No rate differences were found between the control and rule pretraining groups ($p = .87$). Pretraining effects were parallel in the young and old age groups without any hint of an Age × Pretraining × Linear Repetitions interaction ($p = .90$).

Training: RTs by strategies

Mean RTs partitioned by strategies are presented in Figure 5. Because retrieval responses were infrequent early in practice and computation responses were infrequent late in practice, statistical analysis was based on 40 of 60 participants, removing equal numbers of fast and slow learners, and data were collapsed over pretraining condition. The linear component captured the 91% of the repetitions variance, $F(1, 38) = 62.22$, $p < .01$. Beyond the linear trend, the quadratic trend accounted for 6% additional variance. Overall, RTs were longer for older adults than for younger adults, $F(1, 38) = 5.61$, $p = .02$, and the rate of improvement was slower for older adults, Age × Linear Repetitions interaction, $F(1, 38) = 4.37$, $p = .04$. Consistent with the findings of Experiment 1, computation responses were longer than retrieval responses, $F(1, 38) = 6.60$, $p < .01$; and rates of improvement were not different within age groups for computes and retrieves (Strategy × Linear Repetitions interaction: $p = .41$; Age × Strategy × Linear Repetitions interaction: $p = .90$).

To examine the initial advantage of the rule pretraining group, we performed a restricted analysis of computation RTs by pretraining groups using only the first five training blocks (48 of 60 participants were captured). Mean log computation RTs by age group, pretraining group, and log repetitions are presented in Figure 6A. As in the unrestricted analysis, the age effect was not significant (p =.10), and the linear improvement in RTs for computations was significant, $F(1, 42) = 48.89$, p <.01. The rate of improvement in RTs differed by pretraining groups, $F(2, 42) = 7.95$, p <.01. Decomposition of this interaction exposed a distinct learning trajectory for the rule pretraining group. Because the early responses of the participants in the rule pretraining group were relatively fast, this group had a more shallow rate of improvement in the early blocks compared with the control pretraining group, $F(1, 42) = 15.14$, p <.01, and item pretraining group, $F(1, 42) = 7.47$, p <.01. There was no rate difference between the control and item pretraining groups (p =.35).

Training: Overall RTs

Mean RTs by repetitions in log-log coordinates are presented in Figure 7. Improvement in RTs was significant, $F(1, 52) = 496.15$, p <.01, and the log-linear trend carried 91% of the repetitions variance. Beyond the linear trend, the quadratic trend accounted for 6% additional variance. Overall, RTs were longer for older adults than for younger adults, $F(1, 52) = 68.42$, p <.01, and the rate of improvement was slower for older adults, Age × Linear Repetitions interaction, $F(1, 52) = 56.62$, p <.01. The effects on response times of pretraining (p=.23), the Age × Pretraining interaction (p =.29), the Pretraining × Repetitions interaction (p =.24), and the Age × Pretraining × Repetitions interaction (p =.53) were not significant. There was a significant interaction between pretraining and the quadratic trend for RT improvement, $F(1, 52) = 4.57$, p =.01. This second-order interaction is due to the advantage of the rule pretraining group in the early trials of skill acquisition.

Training: Accuracy of responses

Mean response accuracies by age and condition are shown in Table 2. Overall mean accuracy for producing solutions was 0.92, and accuracies improved with practice, $F(2, 104) = 41.29$, p <.01. Accuracies were not different by age (p >.80) or by pretraining condition (p >.50).

DISCUSSION

Experiment 2 went beyond Experiment 1 to examine the benefits of giving practice with item learning and with rule use on subsequent repetition-based skill acquisition in younger and older adults. Item pretraining served to increase item learning during skill acquisition in both age groups. The pretraining manipulations can be construed as providing partial tests of key aspects of Logan's (1988) and Rickard's (1997) theories. Logan's model predicts that retrieves are more likely to win the race against relatively longer algorithm times. In this experiment, participants in the rule pretraining condition began training with a mean RT of 10 s, and participants in the control condition began training with a mean RT of 15 s. The absence of a difference between the rule pretraining group and the controls in retrievals does not support the idea that a shift is more likely to occur as a function of the magnitude of the discrepancy between compute and retrieval times.

Rickard's (1997) model postulates separate strategy nodes for computation and retrieval. Rickard's model predicts that participants in the item pretraining condition should show enhanced item learning, and our findings provide support for this aspect of Rickard's model. However, Rickard's model also predicts that rule pretraining should prestrengthen the node for computation such that participants in the rule pretraining group should show delayed item learning relative to controls. Our results are contrary to this prediction from Rickard's theory.

The findings of Experiment 2 also served to replicate and extend those of Experiment 1 using a production task. Consistent with the findings of the first experiment, age-related deficits were found for the proportions of retrievals across blocks and for rates of improvement in computation and item retrieval during skill learning. Importantly, as shown in Figure 5, there was a substantial age deficit in rates of improvement in the speed of computation and item retrieval, yet the rates of speedup for computes and retrieves were parallel within age groups. Consistent with the findings of the first experiment, Experiment 2 suggests that a single age-attenuated mechanism can account for the age differences in speed of computing and retrieving solutions.

General Discussion

The results of the two experiments reported here provide a highly resolved description of adult age differences in the acquisition of a novel cognitive skill. In previous studies that have examined age effects in the application of a taught algorithm, it has been reported that overall RTs improve more slowly for older adults than for younger adults (e.g., Charness & Campbell, 1988; Touron et al., 2001). In the larger literature on skill acquisition, it has been shown that such differences in overall RT can be due to (a) the speed of executing the algorithmic operations required for solution (i.e., computational speedup), (b) the speed of retrieving answers to problems from memory, and (c) the number of repetitions required for shifting to a more efficient method for obtaining solutions (i.e., from computation to retrieval).

In an effort to sort through these possibilities, in our studies, participants' replies to strategy probes were used to classify responses as computes or retrieves. This enabled us to identify the age effects in several of the key component processes of cognitive skill acquisition. The latency data for computes and retrieves were transformed block by block so as to expose simple power function exponents as the basis for age and condition comparisons in speedup rates. Further, the data on proportions of retrieves were transformed so as to expose differences in negative-exponential acquisition rates. This component served as the basis for evaluating age and condition effects in the efficiency of item learning.

In Experiment 1, it was demonstrated that skill learning was not influenced by the administration of the strategy probes in either age group. Further, probes clearly differentiated “long” computes from “short” retrieves in both age groups (i.e., participants' reports accurately reflected their actual behavior). These outcomes give confidence in the value of using on-line probes to track the course of skill acquisition in elderly participants.

On the basis of our assessment of these strategy-specific skill components, one of our principal findings was the demonstration of an age-related decline in the transition rate from rule use to retrieval, a large effect seen in both experiments. This age reduction in the transition rate is open to several interpretations. It almost certainly reflects in part a well-documented deficit in the efficiency of building and remembering associations between a problem and its solution (Kausler, 1994; Naveh-Benjamin, 2000).

However, beyond any associative deficit, there are several reasons for believing that older adults also harbor a reluctance to rely on memory retrieval as a strategy for obtaining answers. Such reluctance ties into several broader issues regarding aging and skill acquisition. One issue is that accumulated experience is more likely to result in the persistent use of a particular task strategy or task set for older adults than for younger adults, a phenomenon Touron and Hertzog (2004b) referred to as “behavioral inertia” (e.g., Mayr, 2001). Other issues involve age-related production deficiencies (e.g., Verhaeghen & Marcoen, 1994) and age-related difficulties in recognizing optimal strategies (e.g., Rogers et al., 2000; Touron & Hertzog, 2004a, 2004b). Older adults might also avoid retrieval because of more conservative task response criteria (Salthouse & Somberg, 1982; Hertzog, Vernon, & Rypma, 1993), age differences in on-line performance monitoring (e.g., Dunlosky & Hertzog, 2001), or negative implicit beliefs about memory performance in late life (Lineweaver & Hertzog, 1998; McDonald-Miszczak, Hertzog, & Hultsch, 1995). Further research is needed to clarify the extent to which these alternative mechanisms contribute to older adults' strategy performance over and above deficits in associative memory.

A second major finding from both experiments was that the rates of speedup for computes and retrieves were parallel within age groups, whereas those for older adults were less than those for younger adults. The parallel rates of improvement suggest that a single mechanism may account for speedup in the two strategies, and the age change in this rate points to this mechanism as being an age-sensitive one.

This finding is not so readily interpretable in terms of one of the two major theories of skill learning, the instance theory of Logan (1988, 1992). As developed by its author, the theory rests on an assumption of no algorithmic speedup with training, an assumption clearly out of line with both our data and those of many other investigators. Logan acknowledged the implausibility of the assumption—it was made for the sake of analytic tractability of the resulting equations—but he has yet to offer a theory of computational learning to complement his highly developed theory of item learning. Our finding of equal exponents on these two fronts imposes a strong constraint on any such theory, implying as it does some deep connection between algorithmic fluency and retrieval speed.

Just such a connection lies at the center of Rickard's (1997) component power laws (CMPL) theory of skill learning, and our finding is readily, almost preeminently, interpretable in its framework. A computation in CMPL involves the reduction of a complex problem into simpler parts, each of which is resolved by a retrieval from associative memory (Anderson, 1993, first developed this conceptualization of problem solving). Thus, computational solutions and retrieval solutions are both memory based and differ only in the number of retrieval steps required. Speedup in both cases is attributed to a hebbian-like strengthening of the memory traces involved in each retrieval. The common exponent in the compute and retrieve curves captures the efficiency of this hebbian mechanism.

In CMPL, the use-driven accrual of association strength within the compute and retrieve pathways is the only learning process. Strategy choice and the shift from computation to retrieval depend solely on the strength of the two pathways (plus the fixed strength of the bias parameters alluded to in Experiment 2). Two architectural features of the CMPL network ensure that retrieval solutions will eventually dominate computational solutions even though the former are initially weaker than the latter and that the strengthening operator is common to both: (a) Computes strengthen retrieves but not vice versa, and (b) retrieves actively inhibit computes but not vice versa. (Both asymmetries reflect the network's preference for one-step as opposed to multistep solutions.)

Given the architecture and learning dynamics of the CMPL network, growth in retrieval solutions is determined entirely by the speedup in compute and retrieve times. (More strictly, both are determined by the underlying strength variables.) This interdependence allows a particularly powerful characterization of the age differences observed in our experiments. A decline in the efficiency of the mechanism responsible for strengthening connection weights (see Li, Lindenberger, & Frensch, 2000, for a similar proposal) can simultaneously explain the lessened improvement in processing times and the slower growth in retrieval solutions of older adults.

This is basically an association deficit, and it appears to obviate the need to postulate strategy differences in the elderly, as we have done earlier in the discussion. What needs to be said here is that this single-deficit account of the performance decline is only a qualitative one. It remains to be seen whether the exponent changes in the latency curves match the exponential rate changes in the retrieval-probability curves quantitatively. Although the direction of change is concordant in the two sets of parameters, the amount of change may not be. If it is not, a CMPL interpretation of the age changes may still be possible but only at the expense of introducing a second deficit, such as an intensification of the compute-to-retrieve inhibitory connection. This is tantamount to a strategy change (in the conservative direction of lesser reliance on retrieved information, concordant with the findings of Touron and Hertzog, 2004a, 2004b).

Whatever their ultimate explanation, the consistency of the findings for production and verification across Experiments 1 and 2 suggests that the effects of aging on the components of skill learning documented here are robust. Further research should consider whether real-life learning tasks show similar age-related patterns, including parallel slowing across task processes and slowed transition to retrieval solutions. This knowledge might lead to more directed and effective training of older adults, such as is needed for the successful adoption of new technologies.

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APPENDIX

Stimuli Used in Experiments 1 and 2

Experiment 1
- Set 1: True equations
  - 12 # 43 = 75
  - 20 # 54 = 89
  - 29 # 35 = 42
  - 17 # 38 = 60
  - 14 # 42 = 71
- Set 1: False equations
  - 12 # 43 = 60
  - 20 # 54 = 75
  - 29 # 35 = 71
  - 17 # 38 = 42
  - 14 # 42 = 89
- Set 2: True equations
  - 13 # 41 = 70
  - 16 # 53 = 91
  - 22 # 40 = 59
  - 25 # 51 = 78
  - 17 # 44 = 72
- Set 2: False equations
  - 13 # 41 = 59
  - 16 # 53 = 78
  - 22 # 40 = 72
  - 25 # 51 = 70
  - 17 # 44 = 91

Experiment 2
- Set 1: True equations
  - 10 # 44 = 79
  - 12 # 37 = 63
  - 14 # 31 = 49
  - 18 # 49 = 81
  - 21 # 36 = 52
  - 23 # 54 = 86
  - 25 # 39 = 54
  - 29 # 40 = 52
- Set 2: True equations
  - 11 # 34 = 58
  - 13 # 42 = 72
  - 17 # 41 = 66
  - 19 # 37 = 56
  - 20 # 51 = 83
  - 24 # 33 = 43
  - 25 # 48 = 72
  - 28 # 39 = 51
- Set 3: True equations
  - 12 # 47 = 83
  - 15 # 32 = 50
  - 16 # 38 = 61
  - 22 # 35 = 49
  - 23 # 36 = 50
  - 26 # 45 = 65
  - 27 # 52 = 78
  - 30 # 43 = 57

Note. False equations for Experiment 1 were constructed by randomly substituting the correct value of C (given the form $A \# B = C$) with the correct C from a different equation in the set. More than 500 novel equations were constructed randomly (without replacement) by the computer program for the rule-pretraining condition in Experiment 2.