Adults’ Age-Related Differences in Adaptivity of Strategy Choices: Evidence From Computational Estimation

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Four experiments document adults’ age-related changes in computational estimation performance and in adaptivity of strategy choices (i.e., the ability to choose the most precise strategy on each trial). Young and older adults were asked to provide estimates of 2-by-2-digit multiplication problems (e.g., $43 \times 78$) under varying conditions of speed and accuracy emphasis. The main findings showed that (a) older adults provided less accurate estimates and took more time to estimate, especially on the most difficult problems or when using harder strategies; (b) young and older adults had similar strategy preferences; and (c) older adults chose estimation strategies less adaptively than young adults. Implications of these findings for understanding strategic changes during adulthood in a wide variety of cognitive domains are discussed.

The goal of this research was to understand how strategy adaptivity (i.e., our ability to choose the most precise available strategy for accomplishing cognitive tasks) changes with age during adulthood. We pursued this goal in the context of computational estimation tasks to also document age-related differences in this cognitive domain. In computational estimation tasks participants are given arithmetic problems like $47 \times 84$ and have to provide an approximate product (or estimate). As in many other cognitive tasks, participants use several strategies and choose among available strategies on a problem-by-problem basis to provide estimates. Before outlining the logic of the present project, we first review previous findings on age-related differences in strategic aspects of adult cognition. Then, we briefly review previous findings on computational estimation.

Previous Findings on Age-Related Differences in Adults’ Cognitive Strategies

Many definitions of strategies have been given by cognitive psychologists, who view a strategy as “a procedure or a set of procedures for achieving a higher level goal or task” (Lemaire & Reder, 1999, p. 365). Previous works have revealed that young and older adults use several strategies to accomplish cognitive tasks in a variety of domains (see Salthouse, 1991, for a review).

For example, Dunlosky and Hertzog (1998) showed that young and older adults used four different strategies to memorize paired associates: using interactive imagery to link the words, using verbal repetition of the words, making a sentence including both words, and using other strategies. Similarly, Geary and his collaborators (Geary, Frensch, & Wiley, 1993; Geary & Wiley, 1991) found that young and older adults used several strategies to solve simple or complex arithmetic problems such as $42 - 9$ (i.e., countdown, decomposition, columnar retrieval, or other strategies).

Previous works on cognitive strategies have also revealed that strategy distribution (i.e., mean percentage of use of each strategy) may vary across age groups. For example, Dunlosky and Hertzog (2000, 2001) found that older adults used a sentence strategy for paired associates more often than young adults, used a repetition strategy less often than young adults, and used an imagery strategy equally often as young adults. In arithmetic, Geary et al. (1993) found that older adults solved simple subtraction problems such as $9 - 3$ more often through direct retrieval than young adults and that young adults used the addition-reference strategy (like doing $9 - 3 = 3 + 6 = 9$) more often than older adults. Note that, as discussed by Salthouse (1991), age-related differences in strategy use are not always found. For example, similar strategy distributions were observed by Cohen and Faulkner (1983) in mental rotation and linguistic verification tasks.

The final strategic dimension concerns strategy speed and accuracy. In a wide variety of cognitive domains, young people have been found to be almost always faster and more accurate than older adults with each strategy. These age-related differences tend to be larger with the most resource-demanding strategies or when strategies are used to solve more complex problems. To continue with the illustrative examples of memory and arithmetic, we found that...
proportions of correct recall were .63 and .33 in young and older adults, respectively, when they used the sentence strategy to memorize paired associates, and they were .71 and .37 in young and older adults, respectively, when they used the imagery strategy (Dunlosky & Hertzog, 2001). In arithmetic, Geary et al. (1993; see also Charness & Campbell, 1988) found smaller age-related differences to solve simple subtraction problems with retrieval (i.e., response times [RTs] were 905 ms and 1,056 ms in young and older adults, respectively) than with addition-reference strategy (i.e., RTs were 1,195 ms and 1,203 ms in young and older adults, respectively).

One of the least investigated strategy dimensions in the aging literature concerns adaptivity of strategy use. As discussed in detail by Schunn and Reder (2001), strategy adaptivity refers to individuals’ changing their strategy use in response to task-relevant factors to increase levels of performance. These factors characterize task parameters and include, among others, problem and strategy characteristics as well as situational constraints (e.g., speed or accuracy pressures). Adaptive strategy choice has been extensively investigated in young adults and is one of the hallmarks of human cognition. People vary their strategy use in response to problem characteristics (Campbell & Fugelsang, 2001; LeFevre et al., 1996), strategy characteristics (Lemaire & Lecacheur, 2001; Siegler & Lemaire, 1997), their own competence (Jordan & Montani, 1997; Lemaire & Lecacheur, 2002a), and task instructions (Gutentag, 1984; Luwel, Verschaffel, Onghena, & De Corte, 2003). Adaptive strategy choices have been observed in such diverse populations as infants (Adolph, 1995), preschoolers (Geary & Burlingham-Dubree, 1989), school-age children (Lemaire & Fayol, 1995), young adults (LeFevre et al., 1996), and older adults (Geary & Wiley, 1991). They are also present in such diverse domains as arithmetic, serial recall, question answering, sentence verification, reading, reasoning, and naïve physics (Ashcraft, 1995; Fugelsang & Thompson, 2000; Glucksberg & Miscloskey, 1981; Hasher & Zacks, 1979; Jacoby & Dallas, 1981; Schunn & Reder, 2001; Stone & Van Orden, 1992).

Age-related changes in adaptive strategy choices have been well documented in children (see Siegler, 1996, for a review). However, little is known regarding these changes in adults. Previous research suggests that older adults are able to adapt strategies to different task parameters. For example, Siegler and Lemaire (1997) investigated how young and older adults chose between mental arithmetic and a calculator to solve complex arithmetic problems such as $47 \times 89$. They found that both age groups used the calculator more often on hard problems (e.g., $47 \times 89$) than on easy ones ($34 \times 10$) and more often when the calculator enabled them to be faster than mental arithmetic. This was also found by Lemaire and Lecacheur (2001) in their study of between-currency conversion strategy choices and by Geary and his collaborators in their study of simple and complex arithmetic strategies (Geary et al., 1993; Geary & Wiley, 1991). As another example, Dunlosky and Hertzog (1998, 2000, 2001; see also Rogers, Hertzog, & Fisk, 2000) found that both young and older adults varied their strategies to encode word pairs in associative memory tasks to both the type of items they tried to learn and the rate of item presentation. Such variations in older adults’ strategy use have also been reported in diverse decision-making and problem-solving tasks (Chasseigne, Grau, Mullet, & Cama, 1999; Hartley, 1986; Johnson, 1990).

Although these studies have shown that adults of varying age are able to use different strategies to accomplish a cognitive task, no information is available regarding age-related differences in strategy adaptivity. Therefore, the present project was carried out to determine whether young and older adults are equally able not only to use several strategies while accomplishing a cognitive task but also to choose the most efficient available strategies on each problem. This goal was pursued here in the domain of computational estimation.

Previous Research in Computational Estimation

Computational estimation is defined as finding an approximate answer to arithmetic problems without computing the exact answer (e.g., $146 + 69 + 48 = 260$; $47 \times 53 = 2500$). Computational estimation is an interesting cognitive activity not only because it is often used in everyday situations in which a rough answer provides a contextually appropriate degree of precision but also because it is an important component of mathematical cognition. It provides information about people’s general understanding of mathematical concepts, relationships, and strategies (e.g., Carpenter, Coburn, Reys, & Wilson, 1976; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Lemaire, Lecacheur, & Farioli, 2000; Rubenstein, 1985; Sowder, 1992; Sowder & Wheeler, 1989).

Computational estimation has been studied in adults of varying computational proficiency (Dowker, 1997; Dowker, Flood, Grifiths, Harriss, & Hook, 1996; Levine, 1982), as well as in children and adolescents (Baroody, 1989; Case & Sowder, 1990; LeFevre, Greenham, & Waheed, 1993; Lemaire et al., 2000; Lemaire & Lecacheur, 2002b; Sowder & Markovits, 1990). In most of these studies, computational estimation has been investigated by asking participants to provide estimates (or approximate solutions) to arithmetic problems (e.g., $457 + 349 = 800$). All previous studies collected precision of estimates (as measured by the difference between estimates and correct answers) and verbal protocols (i.e., participants’ report of how they found the solution), except in a very few studies in which solution times were also collected.

In all the previously cited research, participants used several computational estimation strategies, and they used available strategies with variable proportions in different age groups and on different problem types. For example, Levine (1982) found that adults rounded both operands up and calculated $820 \times 30$ to estimate $815 \times 26$ or they rounded up only one operand (such as when doing $93 \times 20$ to estimate $93 \times 18$). LeFevre et al. (1993) found that adult participants used rounding both numbers more frequently on larger problems (e.g., $36 \times 146$) than on smaller problems (e.g., $8 \times 112$); this was especially true in young children.

Computational estimation strategies have been found to vary in efficacy, as some strategies yield greater speed and more accurate estimates than others. For example, when an experimenter asked children and adults to provide estimates of three-by-three-digit addition problems, Lemaire et al. (2000) found that rounding with decomposition (e.g., doing $400 + 300 + 60 + 60 = 820$ to estimate $459 + 356$) yielded better estimates than truncation (e.g., doing $450 + 350 = 800$) and that participants were quicker when
using truncation than when using rounding with decomposition. All investigators who compare children of different ages have found increased precision of estimates with age.

Overview of the Present Study

None of the previous studies on computational estimation tested older adults. Therefore, we know little about (a) how older adults accomplish computational estimation tasks, (b) whether older adults use several strategies or a single strategy, (c) whether strategy distributions differ in young and older adults, (d) how fast and accurate older adults are relative to young adults, and (e) whether there are age-related differences in the adaptiveness of computational estimation strategy use. To test these age-related differences, we collected data for the present experiments from young and older adults, accomplishing computational estimation tasks in a variety of conditions.

An advantage of using computational estimation to investigate strategy adaptivity and age-related differences in this ability is that it is easy to determine which strategy yields the best estimates on individual problems. This makes it easy to determine whether participants choose the most precise strategy on each trial (i.e., make adaptive strategy choices) and whether there are reliable age-related differences in adaptiveness of strategy choices. For example, suppose the task is to provide an estimate for 29 \times 34 with either the rounding-down strategy (i.e., rounding both operands to the closest smaller decades, like 20 \times 30) or the rounding-up strategy (i.e., rounding both operands to the closest larger decades, like 30 \times 40). The estimate would be closer to the correct product with rounding up than with rounding down. Indeed, percentage deviation of estimates from the correct product is smaller with rounding up (21.7%) than with rounding down (39.1%). By testing problems known to be best solved with one particular strategy and other problems best solved with another strategy, we were able to determine whether participants choose the most efficient strategy on each problem and under which conditions age-related differences are observed in this ability.

In four experiments, young and older adults were asked to provide estimates of two-by-two-digit multiplication problems (e.g., 43 \times 78). Age-related differences in computational estimation performance and strategy preferences were examined in different conditions of speed and accuracy pressures and for different types of problems. Moreover, age-related differences in adaptivity of strategy use were investigated by comparing the adaptivity of strategy choices (or the ability to choose the most accurate strategy on each trial) in each age group.

Experiment 1

Method

Participants. Thirty young adults (16 women) and 30 older adults (17 women) participated in Experiment 1 (see participants’ characteristics in Table 1). The young adults were undergraduate students from the University of Provence (Aix-en Provence, France) and received course credit for their participation. Older adults were volunteers recruited from the community who were given a short book in French on cognitive aging, written by the first author (Lemaire, 1999), to thank them for their participation. As can be seen in Table 1, young and older adults were matched on the number of years of formal education, arithmetic fluency, and self-rated health.

Stimuli. The stimuli were 144 multiplication problems presented in standard form (i.e., \(a \times b\)) with the operands \(a\) and \(b\) being two-digit numbers. All problems involved one operand with its unit digit smaller than 5 and the other larger than 5. To test age-related differences in participants’ abilities to choose the strategy that provides the best estimate on each problem, the set of 144 problems included two sets of 72 matched problems. On the basis of how precise estimates for each problem were for each trial (i.e., make adaptive strategy choices) and whether there are reliable age-related differences in adaptiveness of strategy choices, we were able to determine whether participants choose the most efficient strategy on each problem and under which conditions age-related differences are observed in this ability.

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<table>
<thead>
<tr>
<th>Table 1: Participants’ Characteristics in Experiments 1–4</th>
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<tr>
<td>Variable</td>
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<tr>
<td>Experiment 1&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Experiment 3&lt;sup&gt;c&lt;/sup&gt;</td>
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Note. Health was self-rated by individuals on a scale from 1 (poor) to 7 (excellent). Dashes indicate that \(F\) is not available. MHVS = French version of the Mill-Hill Vocabulary Scale (Raven, 1951); MMSE = Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975); Arithmetic fluency = Score obtained on a paper-and-pencil arithmetic test in which participants have to solve as many basic arithmetic problems (e.g., 47–32) as possible in 8 min. None of the older adults obtained an MMSE score lower than 27; therefore, none were excluded.

<sup>a</sup><sup>df</sup> = 1, 38, \(p < .01\).
<sup>b</sup><sup>df</sup> = 1, 180, \(p < .01\).
<sup>c</sup><sup>df</sup> = 1, 38.
<sup>d</sup><sup>df</sup> = 1, 94, \(p < .01\).
<sup>df</sup> = 1, 38.
were 18.1% (range between correct products and estimates for rounding-down problems and rounding-up strategies, respectively. Mean percentage deviations between correct products and estimates for rounding-up problems were 24.9% (range = 13.8%–39.2%) and 17.4% (range = 8.5%–31.6%) when using the rounding-down and rounding-up strategies, respectively. Similarly, mean percentage deviations between correct products and estimates for rounding-up problems were 24.9% (range = 13.8%–39.2%) and 17.4% (range = 8.5%–31.6%) when using the rounding-down and rounding-up strategies, respectively. Matching these percentage deviations was necessary because having one strategy with mean percentage deviations smaller on average than those of the other strategy might artifactually lead participants to use the former strategy most often. When one strategy was the best on a given problem, the estimate provided by that strategy was closer to the correct product than the estimate provided by the other strategy.

Rounding-down and rounding-up problems were also matched (a) on the size of the larger operand, (b) on the side of the operand with the smaller unit digit, and (c) on the size of the correct products. The larger of the two operands was the first multiplicand (e.g., 53 × 28) in half of the problems and the second (e.g., 27 × 69) in the other problems; the operand with the smaller unit digit was first (e.g., 42 × 57) in half of the problems and second (e.g., 46 × 52) in the other problems. Size of correct products was on average 2,903 (range = 851–6,264) and 2,988 (range = 912–6,636) for rounding-down and rounding-up problems, respectively.

Given certain effects that are known in the domain of mental arithmetic (see Ashcraft, 1995; Dehaene, 1997; Geary, 1994, for reviews), we controlled the following factors: (a) no operand had 0 or 5 as unit digits; (b) digits were not repeated in the same 10 or unit positions across operands (e.g., 43 × 49); (c) no digits were repeated within operands (e.g., 44 × 58); (d) no reverse orders of operands were used (if 53 × 76 was used, then 76 × 53 was not used); (e) no tie problems, such as 32 × 32, were used; and (f) no operand had its closest decade equal to 0, 10, or 100.

Procedure. Before encountering the experimental problems, participants were told that they were going to do computational estimation. Computational estimation was explained as giving an approximate answer to an arithmetic problem that is as close as possible to the correct answer without actually calculating the correct answer. An example was worked out with participants, who were told,

For example, if I have to estimate 78 × 42, I can do 70 × 40 and give 2,800 as an approximate solution to the problem. I can also do 80 × 50, or do anything else that yields an approximate answer.

Then, all participants were told,

You are going to see two sets of 72 problems each, with a break in-between. Your task it to tell me an approximate product for each problem. To estimate the products, you can use either rounding-up or rounding-down strategies, and no other strategies. Rounding-down means that you round each operand down to the closest smaller decade, like when you do 70 × 40 to estimate 76 × 42. Rounding-up strategy means that you round each operand up to the closest larger decade, for example when you do 80 × 50 to estimate 76 × 42. Be careful. Because I don’t want you to give me the exact product but an approximate product, you will not have the time to calculate the exact products, as your estimates should be stated within 7 s.

Instructions also emphasized that participants should do only the initial rounding up or down and should do nothing more (i.e., adding or subtracting small amounts after calculating the product of rounded operands). After an initial practice period, all individuals had no difficulties with either rounding-down or rounding-up strategies and with the 7-s deadline.

At the beginning of the practice trials, some participants wanted to use the mixed-rounding strategy (i.e., rounding one operand down to the closest smaller decade and rounding the other operand up to the closest larger decade). After a few practice problems, all participants understood that this strategy was not allowed. Participants took more than 7 s to provide their estimates on only 21 out of the 8,640 problems (12 in young adults and 9 in older adults). These data points were not included in data analyses.

The experimental problems were presented in 72-point Arial font (black color) in the center of a 14-in. computer screen controlled by a SONY G-FX201 computer. Each trial began when a 1-s ready signal (the word prép, which means “ready” in French) appeared in the center of the screen. Then, the two-by-two-digit multiplication problems were displayed horizontally. The symbol and numbers were separated by spaces equal to the width of one character. Timing of each trial began when the problem appeared on the screen and ended when the experimenter pressed a button on the space bar of the computer keyboard, the latter event occurring as soon as possible after the participant’s responses. If an estimate was not provided after 7 s, the problem was presented in italic font and in red color. Participants were allowed to provide answers once a problem had changed to red italics, although these were not included in data analyses. The experiment was controlled by E-Prime software (Psychology Software Tools, 1999).

After each response, participants were asked, “Which of the two strategies did you use, the rounding-down or the rounding-up strategy?” On each trial, the experimenter recorded participants’ responses and verbal protocols. Problems remained on the screen during verbal protocols, as pilot testing revealed that this made it easier for participants to describe their strategy.

The order of presentation of problems was randomized for each participant. Each participant was permitted a 5-10-min rest between blocks of 72 problems each. Before the experimental trials, participants were given 18 training problems that were similar to (but different from) experimental problems to familiarize themselves with the apparatus, procedure, and task. All participants were tested in one single testing session that lasted approximately between 60 and 90 min.

Results and Discussion

Results are reported in two main parts. The first part examines age-related differences in estimation performance; the second part looks at age-related differences in adaptivity of strategy use. In all results, unless otherwise noted, differences are significant to at least $p < .05$.

Age-related differences in estimation performance. Following previous work on computational estimation (e.g., LeFevre et al., 1993), the accuracy of participants’ estimates was assessed by calculating percentage deviations between estimates and correct products. In an effort to illustrate, suppose a participant used rounding down and gave 3,200 as an estimate for $82 \times 47$. That
participant would be 16.9% \(\{(3200–3854)/3854\} \times 100\) away from the correct product.\(^1\)

Mean solution times and percentage deviations were analyzed with analyses of variance (ANOVAs) by using a 2 (age: young and older adults) \(\times\) 2 (strategy: rounding-down and rounding-up strategies) design, with age as the only between-subjects factor.\(^2\) In all experiments, following Faust, Balota, Spieler, and Ferrarolo (1999), analyses of solution times were also conducted on standardized solution times to control for artifactual interactions involving the age factor because of general slowing. As no interactions involving the age factor were artifactual in the present experiments, we report statistics for raw estimation times.

As can be seen in Table 2, young adults were, on average, 805 ms faster than older adults, \(F(1, 57) = 18.81, MSE = 2,031,876\); and participants were 774 ms faster when using rounding down than when using rounding up, \(F(1, 57) = 137.57, MSE = 256,883\). Finally, the strategy \(\times\) Problem Type interaction was marginally significant, \(F(1, 57) = 3.79, p = .06, MSE = 61,466\). Although the rounding-down strategy was faster than the rounding-up strategy, the strategy difference in speed was larger on rounding-down problems than on rounding-up problems (837 ms vs. 711 ms). These solution-time results were not compromised by speed-accuracy trade-offs, as the only significant effect in corresponding analyses on mean percentage deviations was the Strategy \(\times\) Problem Type interaction, \(F(1, 57) = 408.39, MSE = 2,792\). As expected, if participants used the strategy they claimed to use, then this interaction showed that participants produced better estimates on rounding-down problems (18.9%) than on rounding-up problems (25.9%) while using the rounding-down strategy; they produced better estimates on rounding-down than on rounding-down problems (19.0% vs. 25.9%) while using the rounding-up strategy. No other effects were significant in either estimation latencies or percentage deviations.

**Age-related differences in adaptivity of strategy use.** Although participants were asked to only round and calculate, sometimes they also added or subtracted small amounts after calculating the product of rounded operands or made calculation errors. Therefore, strategy coding was based on verbal protocols rather than on estimates. Both young and older adults used the rounding-down strategy more often than the rounding-up strategy (56%). Examination of individual protocols indicated that none of the young or other adults were biased toward using one strategy on all problems, because no one used a single strategy on more than 90% of the problems.

Participants used the rounding-down strategy more often on rounding-down problems (67%) than on rounding-up problems (45%). This problem-type difference in strategy use was larger for young (69% vs. 39%) than for older participants (61% vs. 51%). The ANOVAs on mean percentage of use of the rounding-down strategy involving a 2 (young and older adults) \(\times\) 2 (problem type: rounding-down and rounding-up problems) design, with repeated measures on the last factor, revealed no effect of age \((F < 1); significant effects of problem type, \(F(1, 58) = 36.56, MSE = 386.93\); and of Age \(\times\) Problem Type, \(F(1, 58) = 5.12, MSE = 386.93\). As suggested by performance data, participants used rounding down more often, presumably because it was easier to execute. Task analyses suggest that rounding down involves fewer processes: Participants do not need to increment decade digits; they calculate the product of decade digits that are displayed on the computer screen, and computations involve manipulating digits of smaller size.

Age-related differences in strategy distribution across problem type suggest that young and older adults differed in adaptivity of strategy use. Adaptivity of strategy use was defined as using strategies when they yielded the best estimates. For each problem and each participant, adaptive use of a given strategy was coded 1 if the strategy that was used yielded the best estimate on a given problem, and 0 otherwise. Young adults used strategies when they yielded the best products more often than older adults (65% vs. 57%), \(F(1, 58) = 5.12, MSE = 397.16\).

The next series of analyses was aimed at further examining bases for participants’ strategy choices and checking for the possibility that age-related decline in strategy adaptiveness arose from each age group choosing strategies on different bases. To achieve this end, we ran stepwise regression analyses of the percentage of

\(^1\) We also calculated mean percentage errors. Incorrectly executed strategy on a given problem was coded 1, and 0 otherwise. Execution of a given strategy would be considered incorrect if the estimate differed from the expected product given the strategy that was used. For example, an estimate of 3,100 on 82 \(\times\) 47 with rounding down would be incorrect; an estimate of 3,200 would be correct. Finally, we calculated mean percentage deviations between estimates and correct products given the strategy that was used. For example, a participant giving 3,200 as an estimate for 82 \(\times\) 47 while using rounding down would be 0% away from estimate expected from rounding down; percentage deviation would be 3.13% \(\{(3,100–3,200)/3,200\} \times 100\) for an estimate of 3,100 while using rounding down on 82 \(\times\) 47. All three types of accuracy measures yielded exactly the same effects.

\(^2\) As in previous studies of strategies in cognitive tasks (e.g., Lemaire & Siegler, 1995), only participants using a relevant strategy at least three times (participants-based analyses) and items on which the relevant strategies were used by at least 3 participants (items-based analyses) were included in the statistical analyses. At least this many observations are needed to obtain stable estimates of mean speed and accuracy in each condition and on each problem. Data were also analyzed as a function of blocks (e.g., first vs. second half of the experiment or first vs. second vs. third blocks). However, except main effects of blocks (i.e., increased speed and accuracy over blocks), no interaction effects involving the block factor came out significant.
use of rounding down on each of the 144 problems. We examined
the following predictors: (a) each problem’s correct product, (b)
side of the largest operand (coded 1 or 2), (c) side of the operand
with the largest unit digit (coded 1 or 2), and (d) sum of unit digits.
For example, correct product was coded 2394, side of the largest
operand was coded 2, side of the operand with the largest unit was
coded 2, and sum of unit digits was coded 9 for the 42 \times 57
problem. Results are shown in Table 3.

In each age group, two variables accounted for significant
independent variance in the percentage of use of the rounding-
down strategy on each problem: sum of unit digits and correct
product. Thus, strategy choices were based on the same features in
young and older participants. Note that use of sum of unit digits as
the basis of strategy choices makes sense. Indeed, the sum of
unit digits is a good predictor of which strategy will yield the
best product, as shown by a significant correlation between the
sum of unit digits and whether rounding down was the most
precise strategy on each problem (τ = \(-.84\)).

There are several limitations of Experiment 1, however. The
first concerns possible exaggeration of differences in strategy
speed. For example, rounding down was faster than rounding up;
it was also used more often. It is possible that such differences in
strategy speed may either come from or have been exaggerated by
differences in strategy use: The easiest strategy was used more
often, thereby increasing the speed with which participants pro-
vided estimates. The same argument can be made regarding age-
related differences in strategy speed and accuracy. Another limi-
tation of Experiment 1 is that it tested strategy adaptivity as a
function of problem features. As discussed by several authors (e.g.,
Schunn & Reder, 2001; Siegler, 1996), strategy adaptivity involves
calibrating strategy choices to other important determinants of
participants’ performance, such as situational constraints. These
limitations are addressed in Experiment 2.

Table 3
Values in Regression Equations Predicting Strategy Use as a Function of Problem or Strategy
Characteristics (Experiments 1–4)

<table>
<thead>
<tr>
<th>Experiment and age group</th>
<th>Prediction equation</th>
<th>Partial R²s</th>
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<tbody>
<tr>
<td>1</td>
<td>% use of RD = 150.45 - 9.20(unit digits) - .001(product)</td>
<td>.78, .04</td>
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<tr>
<td>Young adults</td>
<td>% use of RD = 100.72 - 4.11(unit digits) + .001(product)</td>
<td>.36, .05</td>
</tr>
<tr>
<td>Older adults</td>
<td>% use of RD = 155.66 - 13.93(unit digits) - .002(product)</td>
<td>.57, .02</td>
</tr>
<tr>
<td>2: No-emphasis condition</td>
<td>% use of RD = 122.61 - 7.02(unit digits) - .002(product)</td>
<td>.52, .03</td>
</tr>
<tr>
<td>Young adults</td>
<td>% use of RD = 110.84 - 4.16(unit digits) + .001(product)</td>
<td>.86, .04</td>
</tr>
<tr>
<td>Older adults</td>
<td>% use of RD = 111.36 - 3.62(unit digits) + .001(product)</td>
<td>.61, .03</td>
</tr>
<tr>
<td>3</td>
<td>% use of RD = 120.44 - 6.78(unit digits) - .04(product)</td>
<td>.78, .06</td>
</tr>
<tr>
<td>Young adults</td>
<td>% use of RD = 96.34 - 4.88(unit digits) - .03(product)</td>
<td>.64, .05</td>
</tr>
<tr>
<td>Older adults</td>
<td>% use of RU = -32.31 + 6.42(unit digits) - .001(product)</td>
<td>.74, .03</td>
</tr>
<tr>
<td>4</td>
<td>% use of RD = -12.70 + 4.36(unit digits) - .002(product)</td>
<td>.65, .03</td>
</tr>
<tr>
<td>Young adults</td>
<td>% use of MR = 58.40 + 4.10(% deviation for MR under NC)</td>
<td>.34</td>
</tr>
<tr>
<td>Older adults</td>
<td>% use of MR = -29.21 + 1.31(% deviation for MR)</td>
<td>.36</td>
</tr>
<tr>
<td>4</td>
<td>% use of rounding down = 154.17 - 9.94(unit digits)</td>
<td>.68</td>
</tr>
<tr>
<td>Young adults</td>
<td>% use of rounding down = 107.44 - 5.32(unit digits)</td>
<td>.45</td>
</tr>
</tbody>
</table>

Note. RD = rounding-down strategy; RU = rounding-up strategy; MR = mixed-rounding strategy; NC = no-choice condition.

Experiment 2

Experiment 2 had three goals. First, we wanted to replicate
findings from Experiment 1, which were, in particular, age-related
similarities in strategy preferences and age-related differences in
strategy execution and adaptiveness of strategy choices. Second,
we tested age-related differences in strategy execution, controlling
for potential influences of strategy use on strategy speed and
accuracy. The third goal of Experiment 2 was to investigate the
role of situational constraints (i.e., different levels of accuracy
pressure) on computational estimation performance in young and
older adults. To achieve these ends, we used the choice–no-choice
method devised by Siegler and Lemaire (1997).

The choice–no-choice method enables independent assessments
of strategy choices and strategy execution. Choices are assessed in
choice conditions in which participants are free to choose among
strategies. Strategy latency and accuracy are assessed in no-choice
conditions in which participants must use a given strategy on all
items. Strategy execution is not confounded with strategy choices.
Unbiased estimates of strategy characteristics (for the sample that
generated the performance) can be obtained when a given strategy
is required for all participants on all trials (i.e., under no-choice
conditions). This makes it possible to objectively assess relative
strategy speed and accuracy, compare strategy speed and accuracy
across different age groups, and examine whether strategy prefer-
ences are associated with relative strategy benefits. That is, par-
ticipants may prefer one strategy over the other because it is easier
to execute, which would be seen in that strategy’s greater speed or
accuracy. By using this choice–no-choice method, strategy use and
execution can be compared among participants of different ages
without running the risk of confounding strategy use and strategy
execution, and the interactions of these two aspects with partici-
pants’ age.
In Experiment 2, eight groups (four each from young and older adults) were asked to provide estimates of answers to two-by-two-digit multiplication problems under two instruction conditions. Participants were asked to be “as fast and accurate as possible” in the so-called no-emphasis condition or to be “as accurate as possible” in the so-called accuracy-emphasis condition. In each age and instruction condition, half the participants were tested under a choice condition (i.e., they could choose between the rounding-down or rounding-up strategies on each trial), and the other participants were tested under both a no-choice–rounding-down condition (i.e., they were required to use the rounding-down strategy on all trials) and a no-choice–rounding-up condition (i.e., they were required to use the rounding-up strategy on all trials).

Of special interest in Experiment 2 was whether young and older adults’ strategy preferences would remain the same under different types of instructions (speed and accuracy emphasis vs. accuracy emphasis), whether young and older adults’ estimation performance would change to the same extent as a function of instruction conditions, and whether adaptivity of young and older adults’ strategy choices would be equally influenced by accuracy instruction conditions.

**Method**

**Participants.** Experiment 2 included 96 young (50 females) adults and 96 older (58 females) adults. Young adults received course credit for their participation, and older adults were volunteers recruited from the community and were given the Lemaire (1999) book to thank them for their participation. Young and older adults were matched on the number of years of formal education, arithmetic fluency, and self-rated health (see Table 1).

**Stimuli.** The stimuli were 80 multiplication problems presented in a standard form (i.e., a \( \times \) b) in which a and b were two-digit numbers, 40 rounding-down and 40 rounding-up problems. Mean percentage deviations between correct products and estimates for rounding-down problems were 15.6% (range = 9.9%–24.4%) and 21.1% (range = 16.9%–30.2%) when using rounding-down and rounding-up strategies, respectively. Mean percentage deviations between correct products and estimates for rounding-up problems were 20.6% (range = 13.8%–32.7%) and 15.7% (range = 9.3%–27.6%) when using rounding-down and rounding-up strategies, respectively. When one strategy was the best on a given problem, the estimate provided by that strategy was closer to the correct product by 5.2% on average (range = 1.3%–13.9%) compared with the estimate provided by the other strategy. For example, the percentage deviation for a problem like 72 \( \times \) 69 was 15.5 when using rounding down and 12.7 when using rounding up (i.e., strategy difference in percentage deviations was 15.4 – 12.7 = 2.7% for 72 \( \times \) 69). The same other controls (e.g., size of correct product across problem types) and constraints (e.g., no repeated operands) as in Experiment 1 were followed in problem selection.

**Procedure.** The procedure was the same as in Experiment 1, with two differences. First, participants were randomly assigned to one of two groups, one called the no-emphasis group and one called the accuracy-emphasis group. Participants in the no-emphasis group were asked, like in Experiment 1, to be as quick and accurate as possible to provide estimates within 7 s; participants in the accuracy-emphasis group were asked to provide estimates that were as close as possible to the correct products within 7 s.

The second difference in procedure from Experiment 1 concerns the choice–no-choice manipulation. Half of the participants were tested under the choice condition and the other half were tested under the no-choice conditions. Participants in the choice condition were told that they could choose between rounding-down or rounding-up strategies on each of the 80 problems. Half of the participants in the no-choice conditions were first required to use the rounding-up strategy on all problems and then to use the rounding-down strategy on all problems; half of the participants saw the reverse order. After an initial practice period, no participants had difficulties with either strategy. In the no-choice conditions, participants were permitted a 5–10-min rest between blocks of 80 problems.

**Results and Discussion**

**Age-related differences in estimation performance.** This section analyzes strategy execution in both the choice and no-choice conditions. Preliminary analyses revealed no simple or interaction effects of strategy order, indicating that participants being tested under the rounding-up first condition had comparable performance to those tested under the rounding-down first condition. Mean solution latencies and percentage deviations in both the choice and no-choice conditions were analyzed with ANOVAs involving 2 (group: young and older adults) \( \times \) 2 (emphasis: no-emphasis and accuracy emphasis) \( \times \) 2 (strategy: rounding-down and rounding-up strategies) \( \times \) 2 (problem type: rounding-down and rounding-up problems) designs, with repeated measures on the last two factors. Mean solution times and percentage deviations for each estimation strategy in each age group are presented in Table 4.

Analysis of choice-condition speed showed significant main effects of age, \( F(1, 81) = 34.34, MSE = 2,573,149 \); strategy, \( F(1, 81) = 75.14, MSE = 419,726 \); and problem type, \( F(1, 81) = 14.07, MSE = 93,695 \); as well as an Emphasis \( \times \) Strategy interaction, \( F(1, 81) = 4.41, MSE = 419,726 \). As can be seen in Table 3, young adults were 481 ms faster than older adults; rounding-down problems were solved more quickly than rounding-up problems (3,745 ms vs. 3,620 ms); and rounding down was 470 ms and 749 ms faster than rounding up under accuracy-emphasis and no-emphasis conditions, respectively. Analysis of mean percentage deviations showed no speed–accuracy trade-offs, as there was only one significant interaction between problem type and strategy, \( F(1, 81) = 354.64, MSE = 8.47 \). This interaction showed that percentage deviations were smaller on rounding-up than on rounding-down problems (17.1% vs. 22.3%) when solved with the rounding-up strategy, and they were smaller on rounding-down problems than on rounding-up problems (16.6% vs. 23.2%) when solved with the rounding-down strategy.

In the no-choice condition, analysis of solution times showed significant main effects of age, \( F(1, 92) = 6.75, MSE = 105,528 \); strategy, \( F(1, 92) = 456.62, MSE = 268,575 \); emphasis, \( F(1, 92) = 15.57, MSE = 1,015,528 \); and problem type, \( F(1, 92) = 12.69, MSE = 18,095 \). The only interaction that came out significant was between strategy and problem type, \( F(1, 92) = 26.27, MSE = 19,161 \). As can be seen in Table 4, young adults (2,681 ms) were faster than older adults (2,766 ms). All participants were faster (a) under the no-accuracy emphasis (2,521 ms) than under the accuracy-emphasis (2,927 ms) condition, (b) with the rounding-down strategy (2,159 ms) than with the rounding-up strategy (3,289 ms), and (c) when solving rounding-down problems (2,699 ms) than when solving rounding-up problems (2,749 ms). Finally, rounding down was faster than rounding up on rounding-down problems, and the reverse was true on rounding-up problems.

Analysis of no-choice percentage deviations revealed main effects of emphasis, \( F(1, 92) = 5.15, MSE = 0.95 \); strategy, \( F(1,
vs. 16.0%). No other effects were significant either in solution times or in percentage deviations.

Participants used the strategies they were required to use under each no-choice condition, then rounding down yielded better estimates than rounding up on rounding-down problems (15.8% vs. 18.6%) problems. Finally, as expected, if participants used the strategies they were required to use under the no-emphasis condition, the required strategy was not used when participants matched estimates from the alternative strategy. For example, a participant who was considered to have not followed the instructions if he or she provided an estimate of 2,800 while he or she was asked to use rounding up on 43 × 78. In both young and older adults, this concerned less than 1% of the problems. Of these 4 biased participants, 1 young participant who was tested under the no-emphasis condition used rounding down on 100% of trials, another young participant who was tested under the no-emphasis condition used rounding down on 95% of trials. All analyses were run with and without these biased participants. Both sets of analyses yielded exactly the same effects. Therefore, all reported analyses included these biased participants.

Young adults used rounding down more often than older adults (63% vs. 53%), \( F(1, 92) = 6.25, MSE = 836.60 \). Participants used it less often under the accuracy-emphasis condition than under the no-emphasis condition (48% vs. 68%), \( F(1, 92) = 21.04, MSE = 836.60 \), and they used it more often to solve rounding-down problems than rounding-up problems (66% vs. 50%), \( F(1, 92) = 100.39, MSE = 123.80 \). It was most interesting to note that two interactions were also significant: Problem Type \( \times \) Emphasis Condition, \( F(1, 92) = 30.49, MSE = 123.80 \), and Age \( \times \) Emphasis Condition \( \times \) Problem Type, \( F(1, 92) = 6.84, MSE = 123.80 \). Participants used the rounding-down strategy on rounding-down problems more often than on rounding-up problems, under both the accuracy-emphasis (71% vs. 39% for young adults and 51% vs. 33% for older adults) and no-emphasis (75% vs. 68% for young adults and 68% vs. 59% for older adults) conditions. However, the difference in using rounding down on each type of problem was smaller under the no-emphasis condition, and this was especially the case in young adults. The Age \( \times \) Emphasis condition (\( F < 1 \)) and Age \( \times \) Problem Type interactions (\( F = 3.17 \)) were not significant.

Age-related differences in strategy use. Overall, participants used the rounding-down strategy most often (58%). Examination of strategy distribution across participants revealed that only 4 participants showed single-strategy bias, when single-strategy bias is defined as using one strategy on more than 90% of the problems. Of these 4 biased participants, 1 young participant who was tested under the no-emphasis condition used rounding down on 100% of trials, another young participant who was tested under the no-emphasis condition used rounding down on 95% of trials, and 2 older participants who were tested under the no-emphasis condition used rounding down on 95% of trials. All analyses were run with and without these biased participants. Both sets of analyses yielded exactly the same effects. Therefore, all reported analyses included these biased participants.

Table 4

Mean Estimation Times (in Milliseconds) and Percentage Deviations for Each Strategy as a Function of Emphasis Condition and Problem Type in Young and Older Adults (Experiment 2)

<table>
<thead>
<tr>
<th>Group × Problem Type</th>
<th>Estimation time</th>
<th>Percent deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rounding down</td>
<td>Rounding up</td>
</tr>
<tr>
<td></td>
<td>Emphasis</td>
<td>No emphasis</td>
</tr>
<tr>
<td>Young adults</td>
<td>2,819</td>
<td>2,775</td>
</tr>
<tr>
<td>Older adults</td>
<td>4,119</td>
<td>3,621</td>
</tr>
</tbody>
</table>

No-choice condition

Young adults

<table>
<thead>
<tr>
<th>Problem Type</th>
<th>Estimation time</th>
<th>Percent deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rounding-down problems</td>
<td>2,184</td>
<td>1,820</td>
</tr>
<tr>
<td>Rounding-up problems</td>
<td>2,308</td>
<td>1,977</td>
</tr>
<tr>
<td>Older adults</td>
<td>2,432</td>
<td>1,958</td>
</tr>
<tr>
<td>Rounding-down problems</td>
<td>2,514</td>
<td>2,078</td>
</tr>
</tbody>
</table>

\(^3\) In both Experiments 2 and 3, our no-choice manipulation check was run by calculating percentage use of no-choice strategies from participants’ estimates. The required strategy was not used when participants’ estimates matched estimates from the alternative strategy. For example, a participant was considered to have not followed the instructions if he or she provided an estimate of 2,800 while he or she was asked to use rounding up on 43 × 78. In both young and older adults, this concerned less than 1% of the problems.
tions was larger in younger than in older adults, as shown by the significant Age × Condition interaction, \( F(1, 92) = 6.82, MSE = 59.09 \). The mean percentage of using the strategy that yielded the best estimates increased from 53% to 66% from the no-emphasis to the accuracy-emphasis condition in young adults, and it increased from 54% to 59% in older adults.

Next, as in Experiment 1, we ran stepwise regression analyses of the percentage of use of rounding down on each of the 80 problems in the choice conditions of each Age × Emphasis condition. Predictors were each problem’s correct product, side of the largest operand, side of the operand with the largest unit digit, and sum of unit digits. As can be seen in Table 2, in each Age × Emphasis condition, the same two variables proved to contribute independently to the percentage of variance accounted for: sum of unit digits and correct product. Thus, both young and older participants’ strategy choices were based on the same problem features.

It is possible to argue that some (if not most) of the findings from both Experiments 1 and 2 stem from how computational estimation strategies were investigated. For example, because only two estimation strategies were available to participants, it can be argued that comparable strategy preferences in young and older adults or age-related differences in estimation performance as well as in adaptivity of strategy choices were observed. Moreover, because of the fact that only two estimation strategies were available to participants, it is possible that age-related differences in strategy use and strategy execution were exaggerated or created by the fact that the problems to solve made it more difficult for older adults to use, execute, and choose adaptively among the two available strategies. Such age-related differences may not have appeared if participants could use a mixed-rounding strategy (e.g., rounding one operand up and the other down). Fast research on computational estimation strategies observed that participants use the mixed-rounding strategy (e.g., Dowker, 1997; LeFevre et al., 1993; Lemaire et al., 2000; Levine, 1982). This issue is addressed in Experiment 3.

Experiment 3

Experiment 3 aimed at replicating findings from Experiments 1 and 2 and at extending them to cases in which people choose between more than two strategies. As in Experiments 1 and 2, young and older adults were given two-by-two-digit multiplication problems and had to provide estimates, but this time they were given a choice among three strategies: rounding both operands down to the closest smaller decade (i.e., rounding down), rounding both operands up to the closest larger decade (i.e., rounding up), or rounding the first operand down and the second operand up to the closest decades (i.e., mixed rounding). Then they were presented the same set of problems. On this presentation, they were required to solve all problems by rounding down, rounding up, and mixed rounding, successively. In addition to generalizing results from Experiments 1 and 2 to multiple-strategy situations, Experiment 3 also enabled us to determine whether strategy performance under no-choice conditions was a significant predictor of strategy use.

Method

Participants. Experiment 3 included 48 young (22 female) and 48 older (26 female) adults. Young adults received course credits and older adults received the Lemaire (1999) book for their participation. As in previous experiments, the two age groups were matched on number of years of education and on self-rated health, as well as on arithmetic and verbal fluencies.

Stimuli. The stimuli were 40 multiplication problems presented in a standard form (i.e., \( a \times b \)) in which \( a \) and \( b \) were two-digit numbers: 13 rounding-down, 13 rounding-up, and 14 mixed-rounding problems. Mean percentage deviations between correct products and estimates for rounding-down problems were 6.8% (range = 4.4%–13.4%), 29.1% (range = 21.5%–36.6%), and 10.8% (range = 6.8%–15.4%) when using rounding-down, rounding-up, and mixed-rounding strategies, respectively. Mean percentage deviations between correct products and estimates for rounding-up problems were 25.8% (range = 18.9%–31.4%), 7.1% (range = 4.3%–13.8%), and 11.9% (range = 7.7%–19.9%) when using rounding-down, rounding-up, and mixed-rounding strategies, respectively. Finally, mean percentage deviations between correct products and estimates for mixed-rounding problems were 16.3% (range = 7.8%–24.4%), 18.9% (range = 7.1%–19.9%), and 4.3% (range = 1.1%–9.9%) when using rounding-down, rounding-up, and mixed-rounding strategies, respectively. The same controls and constraints as in Experiments 1 and 2 were followed in problem selection.

Procedure. The procedure was the same as in Experiment 2, with three differences. First, all participants were tested under the accuracy-emphasis instructions. They were asked to provide estimates that were as close as possible to the correct products within 7 s. Second, they were allowed to use three strategies: rounding down (i.e., rounding both operands down to the closest smaller decades), rounding up (i.e., rounding both operands up to the closest larger decades), and mixed rounding (i.e., rounding the first operand down to the closest smaller decade and the second operand up to the closest larger decade). Third, each participant was tested under both choice and no-choice conditions. Participants were randomly assigned to one of three no-choice presentation orders: choice/no-choice-rounding-down/no-choice-rounding-up/no-choice-mixed-rounding; choice/no-choice-rounding-up/no-choice-mixed-rounding/no-choice-rounding-down; or choice/no-choice-mixed-rounding/no-choice-rounding-down/no-choice-rounding-up. The choice condition was always presented first so that choices would not be influenced by recency effects from just having used a given strategy on 40 consecutive trials. Before the experimental trials, participants were asked to solve six (different but similar to experimental) problems with each of the three strategies so that they would be familiar with all of them.

Results and Discussion

Age-related differences in estimation performance. Mean solution times and percentage deviations for each estimation strategy are presented in Table 5. One-way ANOVAs of solution times in the choice condition showed no significant effects \((Fs < 1.05)\). Analyses of percentage deviations showed reliable differences in solution times across problem types for both rounding down, \( F(2, 44) = 218.81, MSE = 5.25 \), and mixed rounding, \( F(2, 18) = 11.23, MSE = 4.07 \). Mean percentage deviations were smallest on rounding-down problems when solved with the rounding-down strategy and on mixed-rounding problems when solved with the mixed-rounding strategy.

Analyses of estimation times under no-choice conditions revealed significant effects of age, \( F(1, 94) = 13.53, MSE = 3.602,134 \); strategy, \( F(2, 188) = 218.27, MSE = 349,063 \); problem
type, $F(2, 188) = 3.85, \text{MSE} = 128,733$; Age $\times$ Strategy, $F(2, 188) = 3.26, \text{MSE} = 101,468$; and Strategy $\times$ Problem Type, $F(4, 376) = 2.63, \text{MSE} = 96,261$. Rounding down was the fastest strategy (2,120 ms), followed by rounding up (2,906 ms) and mixed rounding (3,060 ms). Young adults were 467 ms faster than older adults, and this old–young difference was largest when using mixed rounding (611 ms), smallest when using rounding up (215 ms), and in-between when using rounding down (485 ms). These effects were not compromised by speed–accuracy trade-offs, as analyses of no-choice mean percentage deviations showed significant effects of age, $F(1, 94) = 2.82, p = .09, \text{MSE} = 7.54$; strategy, $F(2, 188) = 995.65, \text{MSE} = 6.38$; and problem type, $F(2, 188) = 58.62, \text{MSE} = 4.69$. Mean percentage deviations tended to be larger in older adults than in young adults (14.8% vs. 14.4%); they were smallest with the mixed-rounding strategy (8.2%), largest with rounding-up strategy (18.9%) and in-between with rounding-down strategy (16.7%); they were smallest on mixed-rounding problems (13.6%) and largest on rounding-up problems (14.8%) and on rounding-down (14.8%) problems. The Strategy $\times$ Problem Type interaction was significant, $F(4, 376) = 1.929,08, \text{MSE} = 4.79$. As expected, if people were using the strategy they were instructed to use, then this interaction showed that percentage deviations were smallest on rounding-down problems when using the rounding-down strategy, on rounding-up problems when using the rounding-up strategy, and on mixed-rounding problems when using the mixed-rounding strategy. No other effects were significant.

Age-related differences in strategy use. Both young and older adults used the rounding-down (45%) strategy more often than either the rounding-up (25%) or mixed-rounding (30%) strategy. Examination of individual protocols indicated that only 2 young and 2 older participants used only one strategy on 100% of the problems. Two young and 7 older participants used two strategies on at least three problems, and 44 young and 39 older adults used all three strategies on at least three problems.

Mean percentage use of each strategy was analyzed with separate ANOVAs involving 2 (age: young and older adults) $\times$ 3 (problem type: rounding-down, rounding-up, and mixed-rounding problems) mixed designs with age as a between-subjects factor. Participants used the rounding-down strategy on rounding-down problems (89%) more often than on rounding-up (18%) or mixed-rounding (26%) problems, $F(2, 188) = 228.86, \text{MSE} = 626,26$, and this strategy distribution across problem types differed in young and older adults, as shown by an Age $\times$ Problem Type interaction, $F(2, 188) = 6.88, \text{MSE} = 626,26$. Young adults used rounding down more often than older adults on rounding-down problems (97% vs. 81%) and less often on rounding-up problems (16% vs. 21%) or on mixed-rounding problems (22% vs. 31%). Participants used rounding-up strategy on rounding-up problems (69%) more often than on other problems (3%), and this strategy distribution across problem types differed in young and older adults, $F(2, 188) = 7.89, \text{MSE} = 548.10$. Young adults used rounding up more often than older adults on rounding-up problems (78% vs. 61%) and less often on rounding-down problems (0% vs. 5%) or on mixed-rounding problems (0% vs. 6%). Finally, participants used the mixed-rounded strategy on mixed-rounded problems (70%) more frequently than on rounding-down problems (8%) or rounding-up problems (12%), $F(2, 188) = 158.83, \text{MSE} = 726,69$, and this strategy distribution differed in young and older adults, $F(2, 188) = 8.32, \text{MSE} = 726,69$. Young participants used it more often than older adults on mixed-rounding problems (78% vs. 62%) and less often on rounding-down problems (3% vs. 14%) or on rounding-up problems (6% vs. 18%). These age-related differences in strategy distribution across specific problem type suggest that young and older adults differed in mean percentage use of adaptive strategy, which is indeed what actually happened. Young adults used strategies that yielded the most accurate estimates more often than older adults (62% vs. 54%), $F(1, 94) = 5.93, \text{MSE} = 548.04$.

To examine bases for younger and older adults’ strategy choices, we ran three stepwise problem-based regression analyses, predicting use of each strategy with two types of predictors: problem and strategy features. Sum of unit digits and correct product were chosen as problem features because they proved influential in Experiments 1 and 2. Each strategy’s speed and accuracy under no-choice conditions were chosen as strategy characteristics. For example, to predict percentage use of rounding down, mean percentage deviations and estimation times under no-choice conditions were selected because they characterize strategy performance uncontaminated by strategy selection.
For both rounding-down and rounding-up strategies, two factors contributed to the percentage of variance accounted for in the percentage of strategy use in each age group: sum of unit digits and correct product (see Table 3). For mixed rounding, the same single predictor—percentage deviation of mixed-rounding under no-choice conditions—came out significant in both age groups. As in previous experiments, these results indicate that aging does not result in changing bases for strategy choices.

It is possible to argue that, despite comparable arithmetic skills across age groups, age-related differences in adaptive strategy use would have not been found if young and older adults were equally skilled at executing the specific computational estimation strategies. To address this possibility, we attempted to match strategy execution performance under no-choice conditions across young and older adults. If differences in estimation strategy execution contribute to age effects on adaptive strategy use in our data, when participants are matched in strategy execution under no-choice conditions, these age effects should diminish. Therefore, we averaged the strategy performance under no-choice conditions. To do this, we first transformed mean solution times and percentage deviations into z scores and averaged z scores to have a performance index of strategy execution under no-choice conditions for each participant ($M_{\text{young}} = 0.05, M_{\text{older}} = -0.06$), $F(1, 82) = 5.67, MSE = 0.05$. We then equated young adults and older adults on this performance index by eliminating 1 top-scoring and 1 bottom-scoring participant from each group until the averages of the no-choice performance were equal in both groups. This resulted in eliminating the 6 least performing older adults and the 6 best performing younger adults. Results based on the equated groups of 42 participants each were exactly the same as those based on all participants. That is, young adults used strategies when they yielded the best estimates more often than older adults (62% vs. 53%), $F(1, 82) = 4.83, MSE = 578.59$.

Experiment 4: Control Experiment

The most important and original finding in Experiments 1–3 is decreased adaptivity of strategy choices in older adults. However, Experiments 1–3 all had a 7-s deadline. Such a deadline provides an implicit time criterion that may have led to spurious age-related differences such that, for example, older adults did not have enough time to make the most adaptive strategy choices. To determine whether this deadline resulted in inflated age-related differences in adaptive strategy choices, we ran a control experiment in which participants had no deadline and were asked to provide estimates while choosing between rounding-down and rounding-up strategies on each problem.

### Method

**Participants.** Forty individuals, 20 young adults (12 women) and 20 older adults (11 women), participated in Experiment 4. Young adults received course credit for their participation, and older adults received the Lemaire (1999) book to thank them for their participation. As in Experiments 1–3, none of the young or older adults participated in previous experiments on computational estimation or other arithmetic tasks before this experiment, and both age groups were matched on number of years of education, self-rated health, and arithmetic and verbal fluencies ($F$s < 1).

Stimuli and procedure. Stimuli were the same 80 multiplication problems used in Experiment 2, and the procedure was the same as in the Experiment 2 accuracy-emphasis condition, with two exceptions. First, participants were tested only under the choice condition. Second, there was no deadline. Participants were not told that they had to provide their answers within 7 s, and problems did not change to italics and red color after a delay but retained their original appearance.

### Results and Discussion

Age-related differences in estimation performance. Mean solution and percentage deviations for each estimation strategy, presented in Table 6, were analyzed with ANOVAs by using a 2 (age: young and older adults) × 2 (strategy: rounding-down and rounding-up strategies) × 2 (problem type: rounding-down and rounding-up problems) design, with age as the only between-subjects factor.

Young adults were faster than older adults (5,709 ms vs. 7,149 ms), $F(1, 37) = 5.39, MSE = 15,000,946$. That older adults take slightly over 7 s to provide estimate suggests that the 7-s cutoff in the previous experiments was a bit short, at least as far as executing strategies is concerned. Moreover, the strategy effect was significant, $F(1, 37) = 5.85, MSE = 1,028,570$, showing that participants were faster when using the rounding-down (623 ms) than when they used the rounding-up strategy (6,626 ms). Analyses of estimation accuracy showed main effects of problem type, $F(1, 37) = 24.06, MSE = 90.57$, and of strategy, $F(1, 37) = 17.32, MSE = 127.41$. These two main effects were qualified by a Problem Type × Strategy interaction, $F(1, 37) = 78.93, MSE = 75.53$. This resulted from participants’ being closer from correct products on rounding-down problems while using the rounding-down strategy and on rounding-up problems while using the rounding-up strategy.

Age-related differences in adaptivity of strategy use. Both young and older adults used the rounding-down strategy more often than the rounding-up strategy (53%). None of the participants were biased toward using one strategy on all problems. Participants used the rounding-down strategy more often on rounding-down problems (62%) than on rounding-up problems (45%), $F(1, 39) = 38.07, MSE = 141.53$. This problem-type difference was larger in young (64% vs. 42%) than in older adults (58% vs. 48%), as shown by the significant Age × Problem Type interaction, $F(1, 39) = 5.97, MSE = 141.53$. Moreover, when

### Table 6

<table>
<thead>
<tr>
<th>Problem type</th>
<th>Rounding-down strategy</th>
<th>Rounding-up strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimation time (in ms)</td>
<td>Young</td>
<td>Older</td>
</tr>
<tr>
<td>Rounding down</td>
<td>5,510</td>
<td>6,809</td>
</tr>
<tr>
<td>Rounding up</td>
<td>5,561</td>
<td>7,052</td>
</tr>
<tr>
<td>Percent deviation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rounding down</td>
<td>15.7</td>
<td>16.6</td>
</tr>
<tr>
<td>Rounding up</td>
<td>32.9</td>
<td>39.0</td>
</tr>
</tbody>
</table>
adaptivity of strategy use was analyzed, young adults used strategies when they yielded the best products more often than older adults (61% vs. 54%), $F(1, 39) = 6.45, MSE = 69.77$.

Next, as in Experiments 1–3, we ran stepwise regression analyses of the percentage of use of rounding down on each of the 80 problems in each age group to examine bases for participants’ strategy use. Predictors were each problem’s correct product, side of the largest operand, side of the operand with the largest unit digit, and sum of unit digits. In each age group, the single best predictor was the sum of unit digits (see Table 2), showing that strategy choices were based on the same problem feature in young and older adults.

General Discussion

In the present study, (a) young and older adults did not use a single strategy to accomplish computational estimation tasks; (b) they chose adaptively among several strategies on a problem-by-problem basis; (c) they obtained better performance with some strategies and on some problems; and (d) both age groups were flexible enough to adjust their strategy use and execution to accommodate increased accuracy demands. Moreover, older adults obtained poorer computational estimation performance, especially when they used harder strategies or solved more difficult problems, and chose among strategies less adaptively and systematically than young adults. These findings have important implications for understanding cognitive aging and strategic variations.

Regarding distributions of computational estimation strategies, the present results showed that some strategies are favored (e.g., rounding-down strategy) by both young and older adults. Above and beyond similar strategy preferences, there were age-related differences in strategy distributions, even when we controlled for which strategies are available and for the number of available strategies. For example, young adults used rounding down more often than older adults, although this young–old difference varied with problem type and accuracy-emphasis conditions. Such age-related differences in strategy distributions are consistent with previous findings in other tasks or cognitive domains (e.g., Dunlosky & Hertzog, 2000, 2001; Geary et al., 1993; Verhaeghen & Marcoen, 1994). This suggests that it is not enough to assess strategy repertoire. Age-related differences in strategy distributions are important to understand older adults’ cognition. Only when we assess strategies on a trial-by-trial basis can we compare strategy distributions across age groups and experimental conditions.

In all four experiments we found age-related differences in strategy execution: Older adults obtained poorer computational estimation performance. These age-related differences increased with larger problems and the most difficult strategies. These aging effects on strategy execution correspond to an Age $\times$ Complexity phenomena, robustly found in a wide variety of cognitive activities: Older adults are slower and less accurate in triggering and executing cognitive processes, especially on harder problems (see Salthouse, 1991, 1996, for a detailed discussion). A nice feature of our choice/no-choice design is that contribution of strategy use to age-related differences in performance is kept constant in the no-choice conditions. Even when strategy execution was not contaminated by strategy choices, older adults’ performance was not as good as that of young adults. This means that even when we control for strategy differences, we do not necessarily eliminate age-related differences in cognitive performance.

This study reports the first direct evidence that strategy adaptivity (or strategy selection) is an important aspect of aging. Older adults were less systematic and adaptive in their strategy choices than young adults. Both groups tended to choose the preferable strategies on each problem type, but young adults did this more frequently than older adults.

Decreased strategy adaptivity with age challenges existing theories of strategy selection like the adaptive strategy choice model (or its latest version, SCAD; Shrager & Siegler, 1998), ACT-R (Lovett & Anderson, 1996), the adaptive decision maker (Payne, Bettman, & Johnson, 1993), or RCCL (Lovett & Schunn, 1999). All of these models have in common several core assumptions that are not violated by the present data. All strategy selection models assume that participants choose strategies on a problem-by-problem basis, that each strategy is associated with particular performance, and that participants are adaptive in their strategy choices. The present data on computational estimation are consistent with these assumptions. However, none of these strategy-selection models make direct assumptions accounting for age-related differences in adults’ strategy adaptivity.

Models of strategy selection like SCAD, ACT-R or RCCL assume that strategies are selected as a function of several types of information, namely, strategy success, problem types, and participants’ task representation. For example, according to RCCL (Lovett & Schunn, 1999), participants’ representation include the set of stimulus features individuals use to encode the task environment, to generate a set of possible strategies, and to select a given strategy on a given problem. This suggests that young and older adults differ in strategy adaptivity because they use different sets of features (or weight the same set of features differently) to select strategies. Similarly, within SCAD (Shrager & Siegler, 1998), young and older adults differ in strategy adaptivity because they have different problem–strategy or strategy–performance associations. In the present work, analyses of strategy determinants revealed similar bases (e.g., size of unit digits) for strategy choices in young and older participants. Similarly, relative strategy performance was comparable across age groups so that, for example, rounding down was the fastest strategy in both young and older adults.

ACT-R, SCAD, and RCCL suggest another possibility for age-related differences in strategy adaptiveness. Age-related changes in participants’ history of success with strategies drive age-related differences in strategies. This means that older adults are less adaptive in computational estimation strategy choices because they have less experience with relative success for each strategy. Recall that all of our participants had comparable arithmetic skills, even if similar overall arithmetic skills are no evidence for similar experience with computational estimation strategies. With no direct evidence about such age-related differences, it is impossible to determine whether age-related differences in strategy adaptivity observed here reflect age-related differences in experience with computational estimation or history of success of strategies. Experimentally manipulating this history of success (e.g., Lovett & Anderson, 1996; Lovett & Schunn, 1999) may reveal a contribution of this factor to age-related differences in strategy adaptivity.
Such investigations could entail, for example, comparing strategy adaptivity after experiencing different levels of feedback on strategy success.

Another potential contributor to age-related differences in strategy adaptivity is suggested from the aging literature (e.g., Verhaegen & Marcoen, 1994), namely, processing resources. Processing resources include, among others, working-memory capacities, processing speed, or inhibition capacities. The aging literature is replete with studies reporting age-related differences in processing resources (see Craik & Salthouse, 2000, for one recent review). It is possible that decreased processing resources leads older adults to be less systematic in strategy choices and to be less able to choose the most successful strategy on each problem.

How would decreased processing resources be responsible for decline in computational estimation strategy adaptivity? Two aspects of the computational estimation tasks like those tested here may place great demands on participants’ processing resources: being able to encode the most relevant features (e.g., size of unit digits and size of problems) that are predictive of each strategy being able to encode the most relevant features (e.g., size of unit pants made less adaptive strategy choices because they often demanding than rounding down. It is possible that older partici-

pates in inductive reasoning abilities have been shown to be mediated by age-related differences in processing resources (e.g., Salthouse, Legg, Palmon, & Mitchell, 1990).

Executing estimation strategies is also resource consuming. As present data showed, computational estimation strategies vary in difficulty and in resource demands, with rounding up being more demanding than rounding down. It is possible that older participants made less adaptive strategy choices because they often avoided use of the most consuming strategy when that strategy was the best. We tested 16 young (mean age = 21.4 years, range = 18.70–24.10) and 16 older adults (mean age = 69.9 years, range = 62.10–82.10) in the same computational estimation task and with the same material as in Experiments 2 and 4, with one exception: Participants were asked to say for each problem which of rounding-down or rounding-up strategies yielded the best esti-

mation.4 Results showed that the difference in mean percentage of adaptive strategy choices between young and older adults was marginally signiﬁcant, F(1, 30) = 3.02, p = .09, MSE = 260.69. Young and older adults chose the best strategies on 65% and 63% of the problems, respectively. These data suggest that choosing and executing strategies placed processing-resource demands on older adults heavy enough for them to be less adaptive than young adults in their strategy choices (see also Duverne & Lemaire, 2004; El Yagoubi, Besson, & Lemaire, 2003, in press).

In conclusion, the present studies document age-related similarities and differences in computational estimation. These have been studied with a strategy approach. The results point to the importance of taking strategy differences into account when describing and explaining age-related changes in human cognition. As discussed in detail by several authors (e.g., Rogers et al., 2000; Salthouse, 1991; Verhaegen & Marcoen, 1994), it is possible that strategy differences observed here may be mediated by age-related differences in processing resources. Future research adopting the same type of strategy approach used here may shed important light on the strategy debate in the aging literature and document more precisely the contributions of strategy differences to cognitive aging.

References

4 As in all other experiments, young and older participants were matched on the number of years of formal education (minimum of 12 years), self-rated health, arithmetic, and verbal fluencies (Fs < 1). Also, none of the older adults obtained an MMSE score lower than 27; therefore, none were excluded.

COGNITIVE AGING IN ARITHMETIC


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New Editors Appointed, 2006–2011

The Publications and Communications Board of the American Psychological Association announces the appointment of seven new editors for 6-year terms beginning in 2006. As of January 1, 2005, manuscripts should be directed as follows:

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