Implicit Temporal Tuning of Working Memory Strategy during Cognitive Skill Acquisition

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Abstract

Complex cognitive tasks such as multiple step arithmetic require strategies for coordinating mental processes such as calculation with processes for managing working memory. To be most effective, such strategies must be sensitive to factors such as the time required for calculation. In two experiments, we tested whether people can learn the timing constraints on WM demands, when those constraints are implicitly imposed. We varied the retention period for intermediate results using the well-known digit size effect: The larger the operands, the longer it takes to perform addition. During learning, participants practiced multiple-step arithmetic routines combined with large or small digits. At transfer, they performed both practiced and novel combinations. Practice performance was affected by digit size and working memory demands. However, the transfer performance was not fully explained by the digit size effect or simply by the practice effect. We argue that participants acquired temporal tuning of the WM strategy to the implicit retention interval imposed by the digit size, and kept using the tuning mode to unpracticed data set.

One characteristic of fluent cognitive skill is an individual's ability to organize component skills in a well-coordinated form so that the entire skill can be executed smoothly and efficiently. The coordination of component skills is especially important in a time-constrained situation. Consider a student solving a multiple-column addition problem on a timed test. The student must hold intermediate results from already calculated columns in working memory (WM), while applying an addition rule to solve a new column, making another intermediate result available. Because both maintaining information in WM and applying an addition rule take up cognitive resources (e.g., processing time), coordinating them requires the problem solver's sensitivity to the processing demands of each element. In particular, calculation procedures, WM maintenance, and picking up information from a display must be coordinated such that all information is available in appropriate temporal relations.

The question of the current study is whether people can learn the temporal demands on working memory when practicing multiple-step cognitive skills that require maintaining information temporarily in working memory. Sensitivity to externally-imposed timing constraints has been demonstrated in various task domains. For example, in a recent study of serial choice reaction time tasks, people developed sensitivity to timing constraints, such as inter-stimulus intervals or response-stimulus intervals so that, when learned timing constraints were violated, error rates or reaction times increased (Grosjean, Rosenbaum, & Elsinger, 2001). Sensitivity to timing constraints has also been demonstrated in a cognitively more demanding task, multiple-step arithmetic (Carlson & Stevenson, in press). In this paradigm, participants updated a running total on the basis of a series of arithmetic operations. At each step, participants pressed a key to request a new operand for the next step. The delay between the request and the operand presentation was varied, and the results indicated that people were sensitive to this information. When the delay was long, they requested information earlier than when the delay was short. These studies demonstrate that people can and do learn externally-imposed timing constraints in cognitive tasks. Recent research also shows that individuals adjust their micro-strategies for cognitive-perceptual tasks to achieve small improvements in response time (Peck & Carlson, 1999; Gray & Boehm-Davis, 2000); as Gray and Boehm-Davis (2000) put it, "milliseconds matter."

These earlier studies examined explicit timing constraints, in the sense that intervals are marked by external events controlled by the experimenter. However, in many situations timing constraints may be implicit, in the sense that they are not marked by external events but instead arise from the time required for mental processes. The present study investigated whether people can learn such implicit timing constraints that result from characteristics of input data to which procedural skills, such as mental addition, are applied. To manipulate implicit temporal constraints, we took advantage of the well-known <u>digit size effect</u>: The larger the operands, the longer it takes to perform single-digit addition (Parkman & Groen, 1971). In the context of the multiple-step running arithmetic paradigm described below, the digit size effect implies that the time at which an intermediate result will be available depends on the size of the operands of the current addition.

If an arithmetic routine requires holding information in WM during calculation, the digit size effect will result in differential retention times for this information. According to recent research, the retention period as well as the number of items in WM may affect the quality of representations. When an individual must hold information for later use while performing a mental calculation, the information may degrade due to activation decay while the individual is engaged in calculation (Towse, Hitch, & Hutton, 2000). Individuals performing such problems, therefore, should be sensitive to, and learn, the temporal constraints imposed by the speed of their own calculation processes, especially with relatively high WM demands. This is because different temporal constraints on WM management may require different strategies to efficiently carry out the skills, regardless of whether the strategies are implicit or explicit. Wenger and Carlson (1996) suggested that much of the learning associated with practicing arithmetic routines with consistent structures was due to acquiring efficient strategies for managing working memory. We hypothesize here that a similar phenomenon is involved in learning arithmetic routines with consistent temporal constraints. Because the constraints we examine here are implicit in the application of calculation procedures to particular inputs, rather than explicitly marked by external events, we refer to this idea as the implicit temporal tuning hypothesis.

To test this hypothesis, we constructed the arithmetic routines illustrated in Figures 1 and 2. These routines required that participants perform simple arithmetic calculations and hold intermediate results in working memory over several steps. Each participant in the present experiments practiced two arithmetic routines varying in their working memory demands. One routine required participants to perform four addition steps consecutively and hold each result, before retrieving the results for further calculation (High WM routine). In the second routine, the number of consecutive addition steps before retrieval was only two (Low WM routine). For each routine, operands were selected from a set of small digits (1-4) or a set of large digits (6-9). During practice, the assignment of digit sets to arithmetic routines varied across participants. For half of participants small digits were assigned to the High WM routine and large digits to the Low WM routine, and this assignment was reversed. This design ensured that all participants had an equal practice with each arithmetic routine and with each digit set. However, the assignment of digit sets to routines was constant throughout practice for a particular participant, allowing the possibility that the skill acquired for a particular routine would be temporally tuned to the time required for adding digits of a particular size range.

During transfer, each participant solved problems involving all four combinations of arithmetic routine and digit set. For a particular participant, two of these combinations were practiced and two were novel. Across conditions, then, each combination of arithmetic routine and digit set occurred in transfer both as practiced and as novel. Table 1 summarizes this experimental design.

The implicit temporal tuning hypothesis suggests predictions about both transfer and practice for this design. First, the temporal tuning acquired during practice should carry over to transfer when participants perform novel combinations of arithmetic routines and digit sets. For example, an individual who learns to perform a High WM routine quickly because he or she practices with small digits should perform that routine relatively quickly when it is combined at transfer with large digits. This is the critical case for the implicit temporal tuning hypothesis because the prediction for this case can be contrasted with predictions based simply on digit size and memory load or on practice. An explanation based on digit size and memory load would suggest a pattern of results in transfer that mirrors that seen in practice (see below). An explanation based simply on practice would predict that practiced combinations would be performed best in transfer. However, the implicit temporal tuning hypothesis predicts that the High WM/Large Digits combination will be performed most quickly by participants who practiced the High WM/Small Digit combination, because that combination would produce temporal tuning adjusted to faster additions. A similar prediction can also be made for the

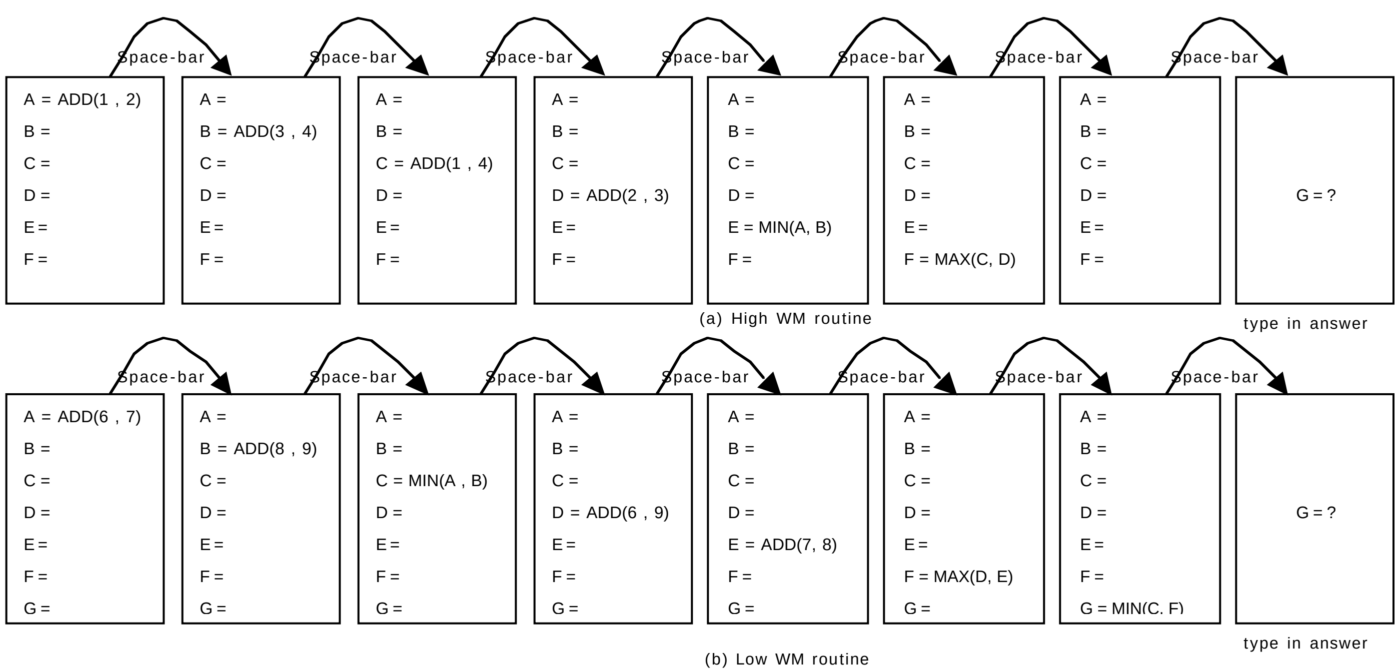

Figure 1. An example of the flow of events on a trial in Experiment 1.

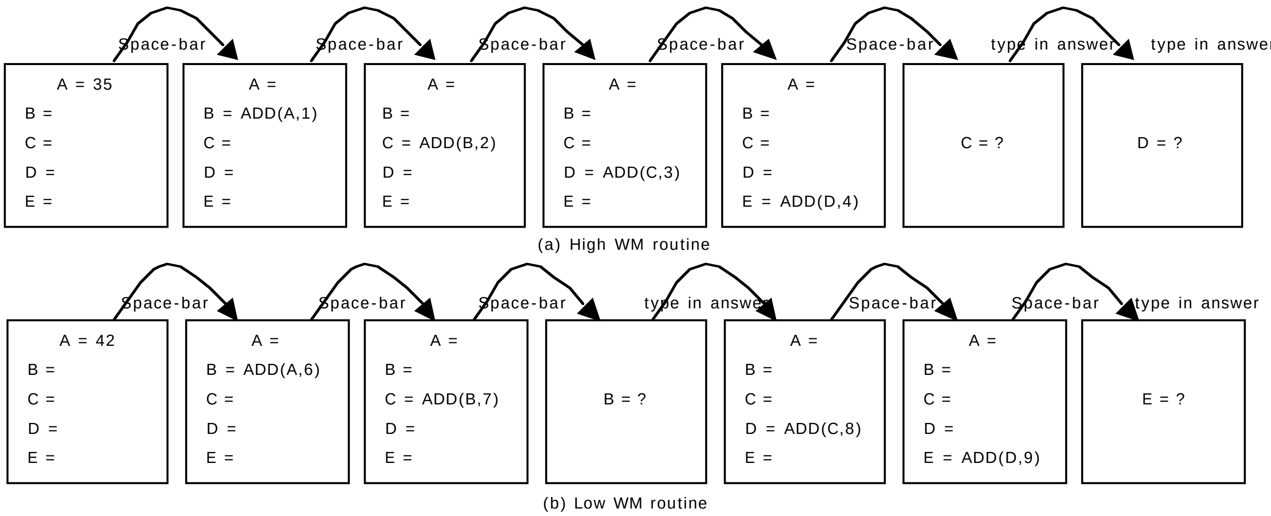

Figure 2. An example of the flow of events on a trial in Experiment 2.

Low WM routine, but temporal tuning may be less critical in this case because of the lower cognitive overhead of the Low WM routine. The implicit temporal tuning hypothesis also makes analogous predictions for other cases – for example, the Low WM/Small Digit combination should be performed relatively slowly by participants who practiced the Low WM/Large digit combination – but these predictions cannot be distinguished from alternative explanations (e.g., unpracticed novel combinations should be performed slower than practiced combinations).

A second prediction of the implicit temporal tuning hypothesis is that during practice the digit size effect should be greater with the High WM routine than with the Low WM routine. This prediction follows from the assumption that the longer retention interval forced by the slower addition of large digits increases the cognitive overhead of coordinating calculation, working memory maintenance, and pickup of information. For example, participants solving the High WM routine with large digits might spend more time to consolidate or rehearse intermediate results because these must be held longer. Alternatively, the working-memory load in the High WM routine might interfere with the retrieval or computation of addition steps (e.g., Anderson, Reder, & Lebiere, 1996). Thus, this practice prediction could also be generated by a capacity account, although the implicit temporal tuning account focuses instead on the organization of strategies for coordinating component processes.

Experiment 1

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In Experiment 1, participants learned two seven-step arithmetic routines, with four addition steps and three comparison steps. At addition (ADD) steps, participants solved addition problems with single digit numbers and stored the intermediate results to use later for comparison steps, in which they compared previous intermediate results. For comparison steps, two operators were used: MIN, which is to choose the smaller value of two numbers, and MAX, which is to choose the larger value of two numbers. The MIN and MAX operators were randomly selected for the comparison steps. Problems were presented individually, step by step. Participants were asked to solve each step mentally and pressed the space-bar to request the next step, until they finished all seven steps. They typed in the final answer (see **Figure 1)**. In the High WM load routine, the first comparison steps appeared after four addition steps. In the Low WM load routine, the first comparison step appeared after two addition steps. Half of the participants practiced the High WM routine with small digits and the Low WM routine with large digits. The other half of participants practiced the High WM routine with large digits and the Low WM routine with small digits. In transfer, participants solved all four combinations (see **Table 1**).

Table 1. Experimental design of Experiments 1 and 2

Practice condition (between-subjects)	Practice		Transfer
	Arithmetic routine	Digit Set	Digit Set/Practice Status
High/Small Low/Large	High WM	Small (1-4)	Small/Practiced Large/Novel
	Low WM	Large (6-9)	Small/Novel Large/Practiced
High/Large Low/Small	High WM	Large (6-9)	Large/Practiced Small/Novel
	Low WM	Small (1-4)	Small/Practiced Large/Novel

Method

Equipment. The displays were generated using MEL (Micro Experimental Lab, Psychology Software Tools, Pittsburgh, PA), and the timing was controlled by an IBM compatible PC.

Task and Procedure. In the beginning of an experimental session, participants were instructed on the task, including the definition of each operator and routine structure. Speed and accuracy were equally emphasized. **Figure 1** shows the procedure for a trial. Each trial began with presentation of a problem frame, which consisted of letters and equal (=) signs. The letters A to G were used to represent variables holding the results of individual steps. The letters and equal signs were differently colored indicating the type of operation (addition or comparison) to be performed during the trial. Participants pressed the space bar to request information for each step. This information appeared next to the relevant step letter and remained for 1,000 ms or until participants pressed the space bar to request information for the next step. After the last step, the problem frame disappeared and a question “G = ?” appeared at the center of the screen. Participants entered the answer using the numeric keypad.

During practice, half of participants performed the High WM routine with small addition problems for which operands ranged 1 to 4, and the Low WM routine with large addition problems for which operands ranged 6 to 9. The other half practiced opposite combinations -- the High WM routine with large operands and the Low WM routine with small operands. For each addition step, two operands were randomly chosen with replacement from the relevant digit sets. Participants were not informed of the manipulation of arithmetic routine-digit set combinations. There were 7 blocks of practice and each block contained 24 trials. Within each block, each routine was sub-blocked so that the first 12 trials would involve one routine, and the second 12 trials would involve another -- from the participant’s point of view, they were presented as separate blocks. The presentation order of routines within blocks was randomized across participants.

There were 3 blocks of transfer with 24 trials each. As in practice, the first 12 trials involved a different routine than the second 12 trials. Within these 12 trials, six random trials involved small problems and the other six involved large problems.

Participant. Thirty-five college students recruited from an introductory psychology class at Pennsylvania State University participated in return for extra course credit. There were seventeen participants in the High/Small-Low/Large practice condition and eighteen participants in the High/Large-Low/Small practice condition.

Results and Discussion

We analyzed three dependent variables: accuracy (whether the final result was entered correctly), mean latency of addition steps (which should be affected by digit size), and mean latency of comparison steps (which should not be affected by digit size). Unless otherwise indicated, we report the High and the Low WM routines independently in both Experiments 1 and 2. Only correct problems contributed data to the latency analyses. The ANOVA model for each routine for practice data was a 2 (digit size) x 7 (practice blocks) mixed factorial. To examine transfer performance, the ANOVA model for each routine was a 2 (practice condition) x 2 (digit size) mixed factorial.

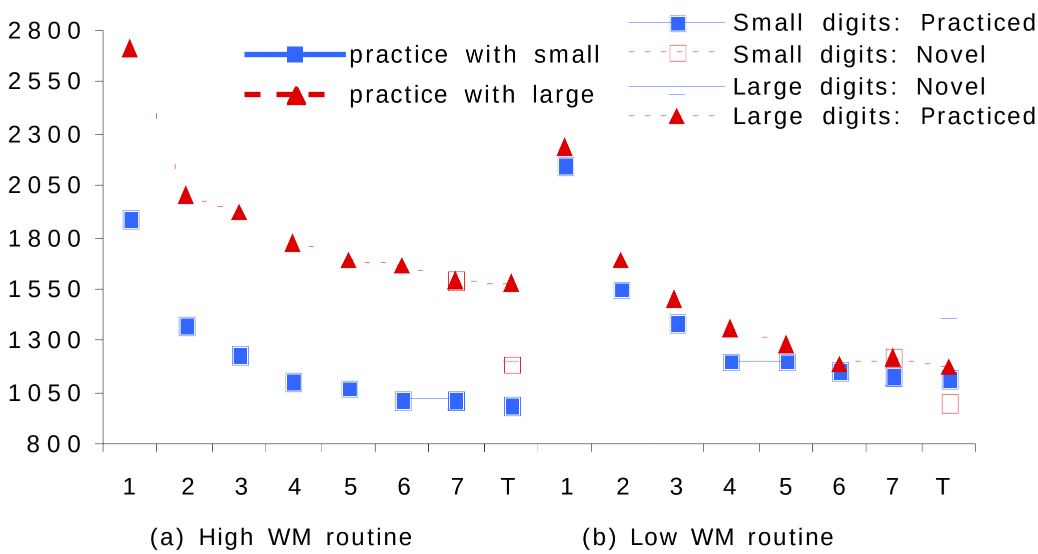

Figure 3. Mean addition latency as a function of practice and digit size with each routine in Experiment 1. The numbers in abscissa indicate practice blocks, and the letter 'T' indicates transfer.

Accuracy. During practice, the accuracy for the High WM routine was higher with small digits (.91) than with large digits (.84), $F(1, 33) = 7.86$, $p < .01$, $MSE = .03$. Accuracy was also a function of practice block, $F(6,198) = 10.51$, $p < .0001$, $MSE = .01$. The interaction between practice block and digit size was not significant, $p > .70$. During transfer, accuracy was higher with small digits (.93) than with large digits (.85), $F(1, 33) = 20.40$, $p < .01$, $MSE = .005$. The main effect of practice condition and the interaction between practice condition and digit size were not significant, $p > .20$.

For the Low WM routine, accuracy during practice was slightly higher with small digits (.87) than with large digits (.83), but this effect was only marginally significant, $p < .06$. Accuracy was a function of practice block, $F(6,198) = 5.14$, $p < .01$, $MSE = .01$. During transfer, no main effects or interaction significantly affected accuracy for the Low WM routine, $p > .20$

Comparison latency. For each routine, the digit size during practice was manipulated between groups. To validate random assignment, we analyzed mean latencies of comparison steps during practice. According to arithmetic literature (Zbrodoff & Logan, 1990), numeric comparison is affected by the distance between numbers not by the size of the numbers themselves. In the current experiment, the difference between two numbers at the MIN or MAX steps did not differ depending on the digit size of the problems. Therefore, there is no a priori reason to be affected by the digit size. For the High WM routine mean comparison latency during practice was only a function of practice block, $F(6,198) = 78.14$, $p < .0001$, $MSE = 154859$. Latency decreased from 2959 ms in Block 1 to 1313 ms in Block 7. For the Low WM routine also, mean comparison latency was a function of practice block, $F(6,198) = 57.27$, $p < .0001$, $MSE = 161185$. Latency decreased from 2599 ms in Block 1 to 1156 ms in Block 7. For neither routine was there a significant effect of digit size, $p > .20$.

Addition latency during practice. **Figure 3** plots mean addition latency for the High WM routine and the Low WM routine during practice and transfer. For the High WM routine, the digit size effect was significant, $F(1, 33) = 17.43$, $p < .01$, $MSE = 1557359$, as was the practice effect, $F(6,198) = 45.58$, $p < .0001$, $MSE = 64367$. Latency decreased from 2320 ms in Block 1 to 1308 ms in Block 7. The interaction between practice block and digit size was not significant, $p > .70$. For the Low WM routine, however, addition latency was only a function of practice block, $F(6,198) = 48.62$, $p < .0001$, $MSE = 96261$. Latency decreased from 2194 ms in Block 1 to 1178 ms in Block 7.

The implicit temporal tuning hypothesis suggests that the need to adjust working memory strategies to the retention interval associated with calculation time should be greater when working memory demands are greater. Consistent with this possibility, the digit size effect was significant for the High WM routine (666 ms), $t(33) = 4.18$, $p < .05$, but not for the Low WM routine (101 ms), $p > .5$.

Addition latency during transfer. Mean transfer latency for addition steps in the High WM routine revealed two main effects (see **Figure 3**). First, regardless of digit size, the participants who practiced the High WM routine with small digits (1115 ms) performed faster than those who practiced with large digits (1384 ms), $F(1,33) = 4.99$, $p < .05$, $MSE = 252863$. Also, participants solved routines with small digits (1093 ms) faster than routines with large digits (1413 ms), $F(1,33) = 43.07$, $p < .0001$, $MSE = 41138$. The interaction was not significant, $p > .20$.

Table 2. Mean accuracy and latency in the final practice block and transfer in Experiment 1

Practice condition	Final Practice Block: Combination	Final Practice Block: Latency (Accuracy)	Transfer: Combination (Practice Status)	Transfer: Latency (Accuracy)
High/Small Low/Large	High WM/ Small	1024 ms (.95)	High WM/Small Practiced	986 ms (.94)
			High WM/Large Novel	1245 ms (.85)
	Low WM/ Large	1224 ms (.85)	Low WM/Small Novel	998 ms (.92)
			Low WM/Large Practiced	1178 ms (.88)
High/Large Low/Small	High WM/ Large	1134 ms (.90)	High WM/Small Novel	1195 ms (.92)
			High WM/Large Practiced	1573 ms (.86)
	Low WM/ Small	1589 ms (.91)	Low WM/Small Practiced	1116 ms (.93)
			Low WM/Large Novel	1446 ms (.92)

Most important, simple effects of digit size effect or practice cannot explain the overall pattern of transfer data. For example, the High WM/Large Digits combination was solved faster by participants who practiced the High WM/Small Digits combination (1245 ms) than by those who practiced the High WM/Large Digits combination (1573 ms), $t(33) = 2.08$, $p < .05$.

For the Low WM routine, participants who practiced with large digits performed faster (1088 ms) than those who practiced small digits (1281 ms), although this difference was not significant, $p > .10$. For this routine, only the digit size effect was significant -- participants solved routines with small digits (1059 ms) faster than routines with large digits (1316 ms), $F(1,33) = 34.33$, $p < .0001$, $MSE = 33143$. The interaction was not significant, $p > .09$.

Discussion. Experiment 1 provided some evidence consistent with the predictions of the implicit temporal tuning hypothesis. First, for the High WM routine, participants who practiced with small digits performed better in transfer on the High WM/Large Digit combination than did those who had practiced this combination throughout. Second, the digit size effect was substantial with the High WM routine but not with the Low WM routine.

The transfer results with the Low WM routine did not follow the same pattern as the High WM routine. It might be that the reduced WM demands of the Low WM routine resulted in less pressure to adjust performance to the temporal constraints imposed by the digit size manipulation. In Experiment 2, we attempted to replicate these results while eliminating some potential ambiguities in the interpretation of Experiment 1.

Experiment 2

The purpose of Experiment 2 was to replicate the results of Experiment 1 and eliminate a potential ambiguity in the interpretation of those results. We suggested that the temporal tuning observed in Experiment 1 should be attributed to participants' experience of the differential execution time for addition steps with small and large digits. However, it is also the case that problems with large digits placed a greater burden on working memory to hold intermediate results. When operands ranged from 6 to 9, the intermediate sums were always two-digit numbers. In contrast, when operands ranged from 1 to 4, the intermediate sums were always single-digit numbers. The two-digit numbers may have posed greater WM demands because verbal materials are held by inner speech and it takes longer to say two-digit numbers than single-digit numbers (Stigler, Lee, & Stevenson, 1986). If so, the WM load may not have been the same for large- and small-digit problems, even though the number of items to be held was the same. These considerations leave open the possibility that it is the time to manage working memory per se rather than the time to perform calculations that may be responsible for Experiment 1 results.

In Experiment 2, the digit size was manipulated for only one operand at each step, and each problem began with a non-zero two-digit starting value. Thus every intermediate result was a two-digit number. Because the effects of interest in Experiment 1 were limited to addition steps, we used simpler routines that simply asked participants to retrieve rather than compare intermediate sums at later steps. **Figure 2** shows the modified routines, and the step-by-step procedure. Every problem began with the starting value, such as “A = 35”. In the High WM routine, participants performed four addition steps and stored the intermediate results in WM, before they were asked to retrieve two of them. The first number to retrieve was always the result of one of the first two steps (i.e., either B or C). The second number to retrieve was always from one of the second two steps (i.e., either D or E). In the Low WM routine, participants performed two addition steps, then retrieved one of these two answers. This procedure was repeated for the second two steps. The two routines were thus equivalent in terms of calculation, intermediate results, and retrieval demands, but differed in the amount and duration of information held in working memory.

We expected to replicate two results from Experiment 1. First, the digit size effect should be greater with the High WM routine than with the Low WM routine. Second, if the implicit temporal tuning hypothesis is correct and Experiment 1 results were indeed due to temporal tuning to calculation time, the transfer performance will reveal tuning to the practiced routine-digit size combination rather than simply reflecting digit size or practice effects.

Method

Task and equipment. The task and equipment were the same as Experiment 1, except that comparisons were replaced by retrievals.

Procedure. Every trial began with presentation of a problem frame with a starting value (see **Figure 2**). The starting value ranged from 21 to 59. The procedure mirrored that of Experiment 1, except for the differences in tasks noted above. The experimental design was the same as in Experiment 1. There were 6 blocks of practice and 2 blocks of transfer. Each block contained 24 trials.

Participant. Twenty-seven college students recruited from an introductory psychology class at Pennsylvania State University participated in return for extra course credit. There were fourteen participants in the High-Small/Low-Large condition and thirteen participants in the High-Large/Low-Small condition.

Results

Accuracy. For the Low WM routine, no main effects or interaction were significant during practice ($M = .80$, $p > .09$) or during transfer ($M = .80$, $p > .06$).

For the High WM routine, practice accuracy was higher with small digits (.61) than with large digits (.42), $F(1, 25) = 9.71$, $p < .01$, $MSE = .16$. Accuracy was also a function of practice block, $F(5,125) = 4.81$, $p < .01$, $MSE = .02$. The interaction between practice block and digit size was not significant, $p > .30$. During transfer ($M = .55$), accuracy was

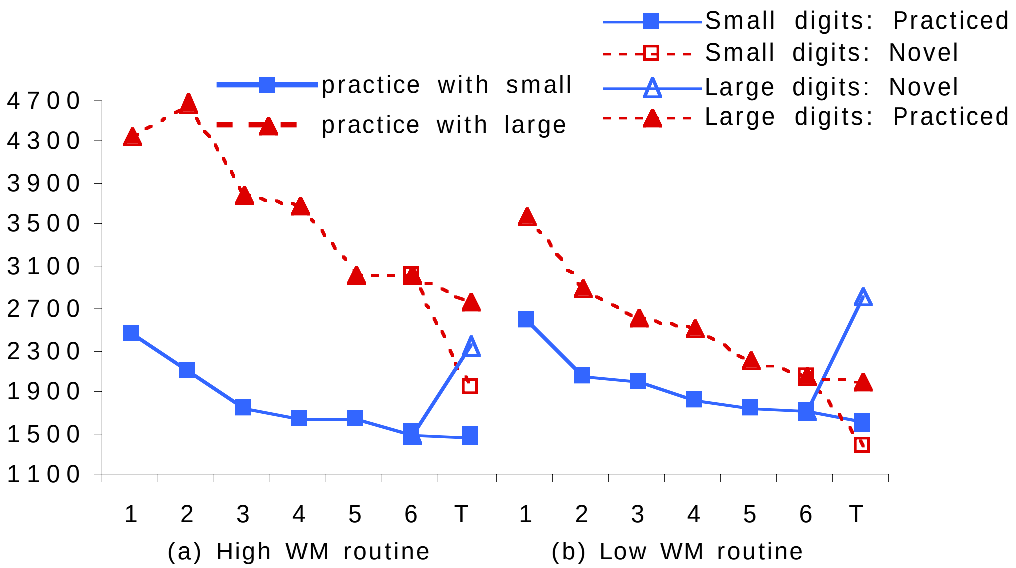

Figure 4. Mean addition latency as a function of practice and digit size with each routine in Experiment 2. The numbers in abscissa indicate practice blocks, and the 'T' indicates transfer.

slightly higher with small digits (.61) than with large digits (.48), but the difference was only marginally significant, $\underline{p} < .06$. The main effect of practice condition was significant, $\underline{F}$ (1,25) = 27.72, $\underline{p} < .0001$, $\underline{MSE}$ = .01. The interaction was not significant, $\underline{p} > .70$.

Latency during practice. **Figure 4** plots the mean latency for the High WM and the Low WM routines as a function of practice block and digit size. The latency for the High WM routine was faster with small digits (1840 ms) than with large digits (3768 ms), $\underline{F}$ (1, 25) = 30.60, $\underline{p} < .0001$, $\underline{MSE}$ = 4914304. As the **Figure 4** suggests, latency was also a function of practice block, $\underline{F}$ (5,125) = 16.30, $\underline{p} < .0001$, $\underline{MSE}$ = 406455, decreasing from 3364 ms in Block 1 to 2234 ms in Block 6. The interaction between practice block and digit size was also significant, $\underline{F}$ (5,125) = 2.96, $\underline{p} < .05$, $\underline{MSE}$ = 406455.

During practice, the latency of the Low WM routine was also faster with small digits (1981 ms) than with large digits (2644 ms), $\underline{F}$ (1, 25) = 9.93, $\underline{p} < .01$, $\underline{MSE}$ = 1788142, and was a function of practice block, $\underline{F}$ (5,125) = 51.37, $\underline{p} < .0001$, $\underline{MSE}$ = 101298. Latency decreased from 3111 ms in Block 1 to 1881 ms in Block 6. The interaction between practice block and digit size was also significant, $\underline{F}$ (5,125) = 3.91, $\underline{p} < .01$, $\underline{MSE}$ = 101298.

As in Experiment 1, a substantially larger digit size effect was found with the High WM routine (1928 ms) than for the Low WM routine (663 ms). This digit size effect was significant for both the High WM routine, t(25) = 5.53, $\underline{p} < .0001$, and the Low WM routine, t(25) = 3.15, $\underline{p} < .01$. This magnitude of this difference in the digit size effect suggests that, consistent with Experiment 1, performing routines with large digits required more complex strategies for managing working memory.

Table 3. Mean accuracy and latency in the final practice block and transfer in Experiment 2

Practice condition	Final Practice Block: Combination	Final Practice Block: Latency (Accuracy)	Transfer: Combination (Practice Status)	Transfer: Latency (Accuracy)
High/Small Low/Large	High WM/ Small	1491 ms (.67)	High WM/Small Practiced	1469 ms (.69)
			High WM/Large Novel	2347 ms (.53)
	Low WM/ Large	2045 ms (.79)	Low WM/Small Novel	1402 ms (.86)
			Low WM/Large Practiced	2003 ms (.82)
High/Large Low/Small	High WM/ Large	3034 ms (.43)	High WM/Small Novel	1941 ms (.55)
			High WM/Large Practiced	2745 ms (.41)
	Low WM/ Small	1704 ms (.84)	Low WM/Small Practiced	1605 ms (.81)
			Low WM/Large Novel	2822 ms (.73)

Latency during transfer. During transfer, addition latency for the High WM routine was faster with small digits (1696 ms) than with large digits (2558 ms), $F(1,25) = 28.65$, $p < .0001$, $MSE = 349125$. Although **Figure 4** suggests a main effect of practice condition, this was only marginally significant, $p < .10$. The interaction between digit size and practice condition was not significant, $p > .80$.

For the Low WM routine, people who practiced this routine with large digits (1702 ms) performed faster than those who practice with small digits (2213 ms), $F(1,25) = 12.29$, $p < .01$, $MSE = 286315$. Also, participants performed the Low WM routine faster with small digits (1500 ms) than with large digits (2398 ms), $F(1,25) = 93.65$, $p < .0001$, $MSE = 119001$. The interaction between practice condition and digit size was significant, $F(1,25) = 10.75$, $p < .01$, $MSE = 119001$. As shown in **Figure 4**, the Low WM/Large Digit combination was performed faster by those who had practiced this combination, while the Low WM/Small Digit combination was performed faster by those who had practiced this routine with large digits.

Discussion

In Experiment 2, the digit size effect was significant in both the High WM and the Low WM routines, and these effects were huge, presumably due to the difficulty of performing these routines. Although the pattern of significant effects did not exactly mirror that in Experiment 1, several results seem to favor the implicit temporal tuning with the High WM routine. First, the digit size effect was greater with the High WM routine than with the Low WM routine. Second, and more importantly, the transfer performance cannot be explained by the digit size effect or by a practice effect alone. For example, as in Experiment 1, the High WM/Large Digit combination was performed faster by participants who practiced the High WM routine with small digits (2357 ms) than by those who practiced the High WM routine with large digits (2775 ms). This is what is expected if working memory strategy was tuned to the faster pace with small problems than with large problems. As indicated earlier, the higher processing load associated with the High WM routine may have resulted in the temporal tuning. These results, which are quite consistent with Experiment 1, cannot be fully explained by considering only effects of WM load, digit size, or practiced combination. We believe that these results are due to implicit temporal tuning, as discussed below.

One concern with the Experiment 2 results is the low accuracy. Our subjective impression, and our participants' reports, indicated that the routines in Experiment 2 were extremely difficult. Moreover, the chance level of performance is very low, well below the observed levels of accuracy. Perhaps the huge digit size effect (1928 ms) in the High WM routine in the current experiment compared with Experiment 1 (666 ms) is related to this high level of difficulty. Nevertheless, the basic pattern of results replicated Experiment 1.

General Discussion

The current study examined the implicit temporal tuning hypothesis, which suggests that individuals will develop working memory strategies that incorporate temporal constraints resulting from the properties of input data. We manipulated these temporal constraints by varying the size of digits presented for addition steps in mental arithmetic routines: Small problems with operands 1 to 4 produce faster calculations than large problems with operands 6 to 9. In general, depending on digit sizes, participants learned different pacing of multiple-step arithmetic routines during practice, as indicated by large interactions between digit size and working memory load. These interactions could be explained by an appropriate capacity model, but the persisting effects in transfer implicate temporal tuning. During transfer, this pacing was sometimes transferred to the routine-data combinations that participants did not practice.

When a substantial portion of the effort required to solve a problem can be attributed to managing working memory, as in our High WM routines, learners appear to adjust their strategies to fit the time required for calculation. This is what we call implicit temporal tuning. This phenomenon was evidenced in both Experiments 1 and 2 by faster transfer performance when the High WM/Large Digit combination was unpracticed rather than practiced, a reversal of the standard finding that transfer is best when a task remains unchanged. When working memory demands are reduced, as in our Low WM routines, transfer performance does not reflect implicit temporal tuning, and shifting to the longer calculation times required by large digits may disrupt performance (**Figures 3 and 4**).

The current study extends the findings that people are sensitive to explicitly imposed timing information (Carlson & Stevenson, in press; Grosjean et al., 2001) to the domain of implicit temporal constraints. The ability to learn the implicit temporal constraints is critical because nearly every aspect of human cognition is constrained by timing information. It takes time to encode stimulus, to apply the relevant stimulus-response mapping rules, and produce the relevant response. This is especially true when the task is complex and cascaded such that previous results are used as input for the current processing. By developing sensitivity to this temporal constraints and an appropriate WM management strategy, cognitive activity can be made more efficient.

We acknowledge that our account is speculative, and that one might wish for stronger data in some statistical comparisons. However, we believe that these results document an important and interesting aspect of how increasing skill results in the adjustment of mental processes to sometimes subtle constraints.

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