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THE ROLE OF WORKING MEMORY AND SENSORIMOTOR SPEED IN ADULT AGE DIFFERENCES IN MENTAL SUBTRACTION*

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Abstract

This study, involving a total of 161 adults between 20 and 79 years of age, investigated age-related differences of cognitive processing in mental subtraction. Aggregated and individual data analyses were conducted to evaluate the relative importance of working memory and sensorimotor speed in adult age differences in mental subtraction. Overall, reaction time and errors increased with the advance of age and arithmetic task difficulty, but the magnitude of age differences in mental subtraction was significantly reduced by statistically controlling measures of working memory and sensorimotor speed. Moreover, there is a larger attenuation of the age-related effects on mental subtraction after control of sensorimotor speed than after control of working memory. However, age-related differences in mental subtraction were not fully mediated by working memory and sensorimotor speed.

Key words working memory, sensorimotor speed, age, mental subtraction.

Mental arithmetic as a mental ability is a critical daily skill, and an important part of mental tests, which is used to identify human intelligence in children, teenagers, and adults. It is known that there is the problem-size effect or problem-difficulty effect in mental arithmetic such as 2 + 3 = 5 or 6 + 9 = 15[1]. In this effect, both reaction time (RT) and errors increase along with an increase in the size or difficulty of the problems; for example, longer RTs in the true or false verification task are observed for 6 + 9 = 15 than for 2 + 3 = 5. Much more studies have explored on how to explain the problem-size effect, and obtained some encouraging results [1,2].

In a small amount of studies on adult age differences in mental arithmetic, however, positive and uniform conclusions about the extent and mechanisms of age-related differences in mental arithmetic are still sparse. Most studies indicated that older adults are slower than young adults in arithmetic involving addition, subtraction, or multiplication[3~6], but a few studies found different and interesting results[7~10]. For example, Allen et al. [7] found no age deficit in the speed of multiplication fact retrieval; Geary et al. [8] and Geary & Lin [9] found older adults were faster at borrowing in complex subtraction than younger adults. These contradictory findings may be attributed to education/cohort effect. In the studies of Allen et al. [7] and Geary et al. [8], the older adults were better educated than the young adults, thus older adults may use a developmentally more mature mix of problem-solving strategies to

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solve arithmetic problems. On the contrary, Salthouse & Coon [6] found that older adults showed a larger borrowing effect than did young adults when the young and older samples were equal in education. However, Allen et al. [10] observed that the age differences in the speed of multiplication fact retrieval were significantly less extreme, consistent with Allen et al. [7], even the young and older samples were roughly matched in education. These results indicated that the cohort effect could not fully explain the age differences in arithmetic.

The differences in data analytical methods among these studies may also result in some disagreements. To study how and why older adults are slower than young adults in mental arithmetic performance, traditional analysis of variance and regression methods are usually used as important analytical procedures. For example, some researchers use a method of distinguishing among different aspects of processing. RTs increase as a function of the size of an answer; this is known as the problem-size effect. Regression of each participant′s RT on problem size yields estimates of the slope—the additional time required per unit increase in answer, and intercept—the RT when the problem size is zero [4, 7, 8, 10]. In such an analysis, the slope is a measure of central processes (e. g., retrieval and decision process) and that the intercept is a measure of peripheral processes (e. g., encoding and response execution) [11, 12]. This method was based on individual data. However, Salthouse & Coon [6] emphasized that regression method is still needed to evaluate whether or not the differences between age groups are larger in some variables than in others. They proposed hierarchical regression analyses as one means of investigating the independence of age-related influences in two or more variables. This aggregated data analytical method, together with ANCOVA (analysis of covariance), and partial correlation etc., was based on calculating the age-related variance in one measure after statistical controlling of the variance in the other. More residual errors in individual data analyses may result in some disagreements in conclusion, thus increasing difficulty when exploring age differences in mental arithmetic.

Age-related differences in cognition may stem from deficits in localized processing modules used by specific tasks or from depletion of central cognitive resources tapped by all tasks and components uniformly or in proportion to their processing requirements [5]. Working memory (WM) and processing speed have been identified as two of such processing resources [13-16].

WM plays a critical role in mental arithmetic tasks [13, 17-20]. Adams & Hitch [21] reported that RT in children′s mental addition has negative correlation with WM span. Jonides [22] proposed that both long-term memory and WM are needed in mental arithmetic tasks. The presentation of a mental arithmetic problem causes representations to be created in both long-term memory and WM. Long-term memory supplies the knowledge, strategies, and skill that are needed to execute a solution. WM, storing partial information simultaneously does the actual computation. The WM system itself is more than just a memory; it includes processing capability as well. Age-related deficits in WM had been proposed to play an important role in age-related cognitive declines [15]. Thus, it is plausible that age-related deterioration of WM underlies the deficit in mental arithmetic.

Some researchers, such as Kail [23, 24] and Salthouse [14, 16], found the important influence of processing speed on children and adult age differences in cognition. Salthouse [14] explored speed mediation of adult age differences in cognition, and indicated that, age-related influences on several measures of memory functioning is greatly attenuated after statistical control of measures of perceptual speed. Furthermore, Salthouse [16] proposed a robust processing-speed theory to account for some of the age-related differences in cognition and strengthened speed mediation of adult age differences in cognition. As for age-mental arithmetic relation, Salthouse & Coon [6] reported that there are large age-related differences in mental arithmetic and those differences appeared to be largely mediated by age-related reductions in a construct related to speed of processing. More detailed information about the role of processing speed in age differences in mental arithmetic still appears to be sparse.

If WM and/or processing speed play critical role in age differences in mental arithmetic, then statistical control of age-related differences of WM and/or processing speed should greatly reduce the age-related variance in arithmetic. On the other hand, most of the studies on age-mental arithmetic relation focused on addition and multiplication, and studies on age-related slowing of mental subtraction processing are still considerably sparse, especially on complex subtraction. For this reason, in this study, we examined adult age differences in mental subtraction and the potential mediating role of cognitive resources in emergence of those differences. First, we investigated whether age-related declines in mental subtraction performance are differential and task dependent. If this is so, the statistical expression of this relationship would be a significant interaction between age and task type of arithmetic. Second, we examined whether age-related slowing of mental subtraction processing could be explained by age-related reduction of processing resources, such as WM and sensorimotor speed (SMS). In statistical terms, that is to say, whether there is a substantial reduction of age effects after controlling for variability associated with these resources. Aggregated and individual data analyses were conducted respectively to evaluate which factor (WM and/or SMS) plays much more, and examine whether SMS and WM fully mediated age-related effect on mental subtraction.

1　Method

1.1　Subjects

Demographic characteristics of the 161 normal participants (83 males and 78 females) ranging from 20 to 79 years of age in this study are summarized in table 1. All participants were from China, divided into 6 age groups such as 20 ~ 29, 30 ~ 39, and so on, with years of education matched (Bonferroni contrast didn't reveal significant difference between any two groups). For each participant, self-assessed health status was excellent or good. Health and education were therefore not considered for all subsequent analyses.

1.2　Procedure

All participants performed three types of tasks, the computation span working memory, digit copying, and mental subtraction on a microcomputer. During the whole test, each of them only typed digit key in the right side of the keyboard, and could finish all of the tasks within 15 minutes.

1.2.1　Computation Span Working Memory　In this task, a series of subtraction problems were presented for the participants to solve by typing digit key while also remembering the answer, in accordance with WM which is usually defined in terms of the simultaneous storage and processing of information [17]. The arithmetic problems were presented in production format, and were all of the form $X - Y =$, with the following restrictions: (a) X and Y were two-digit numbers between 10 and 99; (b) answer to each problem was a single positive integer; (c) the answer to the problem could not be the same for two adjacent problems in a trial.

After reading a brief description of the task, the subjects performed three practice trials, followed by experimented trials. On completion of the designated number of problems, the instructions (asked participants to recall) appeared on the screen. At this point, the participant typed the answer of each problem in the order in which the problem appeared. The number of arithmetic problems increased successively from one, with two trials presented at each sequence length. The program continued as long as the subject was correct on both processing (answering the arithmetic problem) and recall (reporting the answer) on at least one of the two trials at each sequence length. The subject's WM span was defined as the largest number of items in which he or she was correct on both processing and recall in at least one of the two trials.

1.2.2　One-digit Copying　In this task, each of the subjects had to copy a one-digit number by typing digit key as rapidly as possible with 100 percent accuracy limited. The number was randomly produced by microcomputer, and presented visually on the screen. After reading the instruction, the subjects performed two practice trials, followed by ten experimented trials. RT measure of each trial was in the course from the time when the digit appeared on the screen to when the digit had been typed. The computer recorded the copying time in 0.01 second. One-way ANOVA indicated the significant effect of age on one-digit copying RT ($F(5,155) = 14.88$, $MSE = 0.069$, $p < 0.001$). Because the digit copying was postulated to assess SMS [6, 14], and this task was performed with the limitation of 100 percent accuracy, the SMS was defined as a reciprocal of RT of one digit copying.

1.2.3 Mental Subtraction Four mental subtraction tasks, 1000 − 3, 1000 − 7, 1000 − 13, and 1000 − 17, were designed with a serial calculation in which the subjects sequentially subtracted the same prime number (3, 7, 13, and 17) from the number 1000. The subtraction arithmetic was performed after the subject read a brief description of the task. The subtraction problems were presented in production format, with the subjects instructed to answer by typing digit key as rapidly and accurately as possible. Problems were presented as white characters on a dark background in the middle of color monitor controlled by microcomputer. After reading the instructions, the subjects performed two practice trials (e. g., 1000 − 2 and 1000 − 5), followed by experimented trials, 1000 − 3, 1000 − 7, 1000 − 13, and 1000 − 17. In each trial, the subjects sequentially subtracted the same number for five times. RT in 0.01 second and errors were recorded by microcomputer.

In each trial, RT measure of the first calculation was in the course from the time when the problem appeared on the screen to when the full answer had been given, while in the other four calculations, RT measure of each calculation was in the course from the time when the preceding full answer had been given to when this full answer had been given. During calculation, if an error occurred, followed a series of "errors" (e. g., for 1000 − 3, the subject's responses were, 997, 993, 990, 987, 984), only the former (e. g., 997 − 3 = 993) was accepted as an error. After the subject finished all of subtraction tasks, he/she was asked to describe how he/she computed. Each of them reported that he/she only subtracted the prime number (i. e., 3, 7, 13, and 17) for five times. None of them solved the problem by using other non-subtractive strategies such as multiplication. For example, he/she didn't multiply the prime number by five, and then subtract that value.

Subtraction tasks used in this study have higher working memory demands than other easier subtraction tasks used in previous studies, such as 9 − 4 or 72 − 7. Answering the easier problem such as 9 − 4 was generally attributed to retrieving arithmetic fact from memory. Solving the arithmetic problems used in this study, however, consisted of a series of cognitive processes, such as covert production of numbers, retrieving arithmetic facts from memorized tables, execution of a specific calculation procedure such as subtraction and storing data in memory for further operation. Here these cognitive processes may be processed simultaneously. For this reason, the RT from the time when the subject started producing his/her answer to when the full answer had been given may not be pure motor time in the four subtraction tasks.

In order to extract the sensorimotor component which was contained in each subject's RT measures of the four subtraction tasks, each of the subjects merely had to copy a three-digit number (e. g., 915) by typing digit key as rapidly and accurately (termed *three-digits copying task*) as possible after he/she had performed subtraction tasks. The number was randomly produced by microcomputer, and presented visually on the screen. Each subject performed five experimented trials. RT measure of each trial was in the course from the time when the digit appeared on the screen to when all of the three digits had been typed. The computer recorded the copying time in 0.01 second and errors. One-way ANOVA indicated the significant effect of age on three-digits copying RT, $F(5,155) = 18.73$, $MSE = 0.085$, $p < 0.001$, but not on accuracy, $F(5,155) = 0.314$, $MSE = 0.008$, *ns*. According to Donders' subtractive method, the sensorimotor component could be removed from all RT measures of the four arithmetic tasks by subtracting three-digit copying RT as a baseline from the arithmetic RT, and the difference was regarded as a time of calculation, which was used in subsequent aggregated data analyses (i. e., general linear model).

2 Results

2.1 Data Conditioning

Mean values and standard deviations for the measures of performance from WM task, digit copying, and mental subtraction tasks are summarized in table 1.

Table 1　Age, Education, Working Memory Computation Span, Digit Copying, and Mental Subtraction Tasks Including Percentage of Accuracy and Reaction Time in Second as a Function of Age Group

Variables	20 - 29 (n = 32)		30 - 39 (n = 26)		40 - 49 (n = 30)		50 - 59 (n = 26)		60 - 69 (n = 26)		70 - 79 (n = 21)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age (years)	23.8	2.7	33.7	2.8	43.3	2.8	55.6	3.2	63.3	2.1	73.3	3.1
Education (years)	15.3	1.5	14.8	1.9	14.7	1.5	14.9	1.5	15.5	1.3	15.7	0.9
Computation span	7.2	2.2	4.8	2.1	5.0	2.3	5.6	2.7	5.3	2.2	4.1	1.7
One digit copying (S)	0.99	0.18	1.02	0.15	1.12	0.26	1.28	0.24	1.34	0.36	1.51	0.35
Three digits copying												
Accuracy (%)	98.4	4.5	99.6	1.9	98.3	5.3	98.8	4.3	98.5	4.6	98.6	4.7
Time (S)	0.57	0.18	0.60	0.30	0.70	0.29	0.76	0.26	0.73	0.32	1.06	0.40
1000 - 3												
Accuracy (%)	96.8	5.4	94.6	8.1	93.0	9.8	95.4	7.6	88.9	11.7	87.6	11.8
Time (S)	2.37	1.17	3.23	1.59	3.65	1.88	3.84	2.31	3.50	1.81	3.99	1.93
1000 - 7												
Accuracy (%)	95.9	7.1	90.0	8.9	90.6	9.1	88.8	10.7	88.1	13.3	78.6	14.2
Time (S)	3.53	1.45	4.45	1.82	5.02	1.93	5.40	2.72	5.85	2.73	7.70	3.82
1000 - 13												
Accuracy (%)	95.6	7.6	87.7	10.7	85.0	11.1	87.3	12.2	88.8	8.6	81.0	12.2
Time (S)	4.49	2.05	5.18	1.80	6.26	3.90	6.98	3.01	6.75	2.73	9.23	3.34
1000 - 17												
Accuracy (%)	95.0	6.7	90.8	9.8	84.3	11.3	83.1	12.9	85.4	11.4	76.7	12.8
Time (S)	5.61	2.35	6.94	3.72	7.70	4.18	8.88	4.55	9.72	4.96	9.70	4.56

For mental subtraction, all of RT measures in incorrect responses were removed from the total of experimented trials. RT measures of correct responses were used in all subsequent analyses. All of the correlations of RT measures between any two of subtraction tasks were significant ($p < 0.01$, in the range of 0.46 to 0.65, mean $r = 0.53$), while correlations of the accuracy measures between any two of subtraction tasks were also significant ($p < 0.01$) except for correlations between 1000 - 3 and 1000 - 7, 1000 - 3 and 1000 - 17 (in the range of 0.09 to 0.40, mean $r = 0.25$). The correlation between RT and accuracy in each subtraction task wasn't significant except for 1000 - 7 ($r = -0.24$, $p < 0.01$). We used alpha coefficient to estimate the internal consistent reliability within the four subtraction tasks. Alpha coefficients were 0.82 for RT measures, 0.58 for accuracy measures of mental subtraction. The descriptive statistics for RT and accuracy across task difficulty levels of all subtraction tasks are summarized in Table 2.

Introspection of the scatter plots of RT and age in Figure 1 suggests that variability of RT differed across task difficulty levels. Indeed, as presented in Table 2, coefficients of variation (a ratio of standard deviation to mean) ranged from 0.51 to 0.54 for RT measures, and from 0.10 to 0.14 for accuracy measures. Overall, most of the accuracy measures are generally over 70% or greater in each age group.

Table 2　Descriptive Statistics for Reaction Time and Accuracy Across Task Difficulty Levels of Mental Subtraction

Task	Reaction Time (S)			Accuracy (%)		
	M	*SD*	*CV*	*M*	*SD*	*CV*
1000 - 3	3.38	1.85	0.54	93.0	9.6	0.10
1000 - 7	5.17	2.70	0.52	89.3	11.5	0.13
1000 - 13	6.31	3.19	0.51	88.0	11.2	0.13
1000 - 17	7.94	4.29	0.54	86.5	12.1	0.14

Note. *CV* = coefficient of variation, a ratio of the standard deviation to the mean.

2.2　Analysis of Performance Across Tasks: RT

A general linear model was used to evaluate the importance of WM and SMS in age differences in mental subtraction respectively. In this model, age was a six - level between - subjects independent variable, and task difficulty (from the easiest, 1000 - 3, to the most difficult, 1000 - 17) was a four - level repeated measure factor. To estimate the magnitude of the effects we computed partial eta squared (η^2), a ratio of the effect sum of squares to the total sum of squares associated with that effect's error term.

The results of the analysis revealed significant main effects for age, $F(5,155) = 7.86$, $MSE = 16.59$, $p < 0.001$, $\eta^2 = 0.203$; task difficulty, $F(3, 465) = 108.09$, $MSE = 5.151$, $p < 0.001$, $\eta^2 = 0.432$; as well as significant age × task difficulty interaction, $F(15, 465) = 2.08$, $MSE = 5.151$, $p < 0.01$, $\eta^2 = 0.063$. To examine whether age-related slowing of mental subtraction processing can be explained by age-related reduction of WM and SMS, we repeated the analyses with WM and SMS as covariates, singly and together. Inclusion of WM in the model reduced the main effect of task difficulty, $F(3, 462) = 22.55$, $MSE = 5.141$, $p < 0.001$, $\eta^2 = 0.128$. The main effect of age, $F(5,154) = 5.51$, $MSE = 15.731$, $p < 0.001$, $\eta^2 = 0.152$, and the age × task difficulty interaction, $F(15, 462) = 2.01$, $MSE = 5.141$, $p < 0.05$, $\eta^2 = 0.061$, remained essentially unaltered.

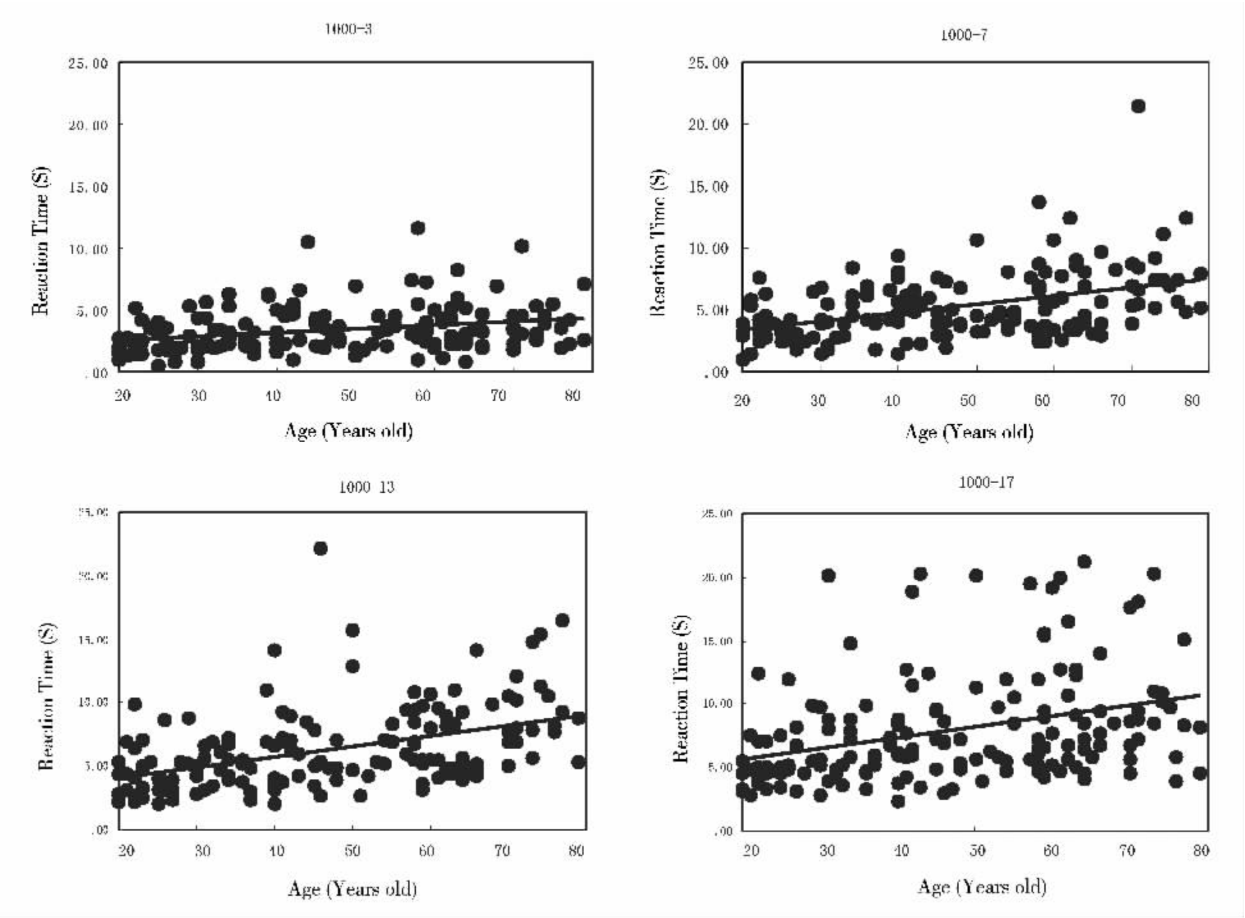

Figure 1 Relationship between reaction time and age in four subtraction tasks as depicted in scatter plots with linear regression lines.

Comparing to the effect of WM, introduction of SMS into the model reduced the main effects of age by more than half, $F(5, 154) = 3.06$, $MSE = 16.194$, $p < 0.05$, $\eta^2 = 0.090$, and task difficulty by more than ten, $F(3, 462) = 5.48$, $MSE = 5.156$, $p < 0.01$, $\eta^2 = 0.034$, as well as the age × task difficulty interaction, $F(15, 462) = 1.53$, $MSE = 5.156$, ns, $\eta^2 = 0.047$. Introduction of both WM and SMS into the model simultaneously, once again reduced the effects of age, $F(5, 153) = 2.45$, $MSE = 15.583$, $p < 0.05$, $\eta^2 = 0.074$, and task difficulty, $F(3, 459) = 5.32$, $MSE = 5.129$, $p <$

0.01, $\eta^2 = 0.034$, as well as the age × task difficulty interaction, $F(15, 459) = 1.57$, $MSE = 5.129$, *ns*, $\eta^2 = 0.049$.

From these results, it can be inferred that, 25.1% (i.e., $[0.203 - 0.152]/0.203 \times 100 = 25.1\%$) of the age-related variance in RT measure of subtraction were attenuated by controlling the variance associated with the WM measure, whereas 55.7% (i.e., $[0.203 - 0.090]/0.203 \times 100 = 55.7\%$) of the age-related variance in RT measure of subtraction were attenuated by controlling the variance associated with the SMS measure. Finally, 36.5% (i.e., $[0.074/0.203] \times 100 = 36.5\%$) of the total age-related effects on RT measure of mental subtraction cannot be accounted for by age-related reductions in WM and SMS.

2.3 Analysis of Performance Across Tasks: Accuracy

A general linear model similar to the one used in RT analysis was applied to the accuracy data. The results of the analysis revealed significant main effects for age, $F(5, 155) = 15.77$, $MSE = 0.015$, $p < 0.001$, $\eta^2 = 0.337$, and task difficulty, $F(3, 465) = 14.97$, $MSE = 0.009$, $p < 0.001$, $\eta^2 = 0.088$, but age × task difficulty interaction was not significant, $F(15, 465) = 1.64$, $MSE = 0.009$, *ns*, $\eta^2 = 0.050$. When individual differences in WM proficiency were taken into account by entering WM as a covariate in the model, the main effect of task difficulty was eliminated by more than three, $F(3, 462) = 4.34$, $MSE = 0.009$, $p < 0.01$, $\eta^2 = 0.027$, and the main effect of age was reduced somewhat, $F(5, 154) = 10.99$, $MSE = 0.014$, $p < 0.001$, $\eta^2 = 0.263$. Comparing to the effect of WM, the main effects of age, $F(5, 154) = 10.49$, $MSE = 0.015$, $p < 0.001$, $\eta^2 = 0.254$, and task difficulty, $F(3, 462) = 1.78$, $MSE = 0.009$, *ns*, $\eta^2 = 0.011$, were eliminated much more when SMS as a covariate was introduced into the model. Introduction of both WM and SMS into the model simultaneously, once again reduced the main effects of age, $F(5, 153) = 8.56$, $MSE = 0.014$, $p < 0.001$, $\eta^2 = 0.219$, and task difficulty, $F(3, 459) = 1.69$, $MSE = 0.009$, *ns*, $\eta^2 = 0.011$.

From these results, it can be also inferred that, 22% (i.e., $[0.337 - 0.263]/0.337 \times 100 = 22.0\%$) of the age-related variance in accuracy measure of subtraction were attenuated by controlling the variance associated with the WM measure, whereas 24.6% (i.e., $[0.337 - 0.254]/0.337 \times 100 = 24.6\%$) of the age-related variance in accuracy measure of subtraction were attenuated by controlling the variance associated with the SMS measure. Finally, 65% (i.e., $[0.219/0.337] \times 100 = 65.0\%$) of the total age-related effects on accuracy measure of subtraction cannot be accounted for by age-related reductions in WM and SMS.

2.4 Individual Data Analysis: Regression of RT on Task difficulty

A glance at the scatter plots of the RT and age across the four tasks suggests that aggregated data analysis may be limited by substantial individual variability. To examine the effects of age and resources indices at the level of the individual, we conducted analysis on individual indexes of performance across the levels of task difficulty (with subtrahend increasing, from 3, 7, and 13 to 17). Because three digit copying task can be acted as a subtraction task in which subtrahend was zero, we used the slope of simple regression of each subject's RT on five subtrahends (zero, three, seven, thirteen and seventeen) as an index of task-dependent slowing. The fit of individual participants' data was good (R^2 ranged from 0.40 to 0.99, with the median $R^2 = 0.81$) and was unrelated to age ($r = -0.027$, *ns*).

The slopes were submitted to a series of hierarchical linear models, in which age, WM, and SMS served as predictors. The amount of age-related variance in slope was examined before and after controlling the variance associated with the measure of WM and SMS, and the difference between the two estimates of age-related variance can be used as an indication of the importance of the controlled variable (WM and SMS).

Results of the hierarchical regression analyses are summarized in Table 3. Entries in the first column of this table indicate the accumulative R^2 in the prediction of the criterion variable after the variable on that row and the variables on immediately preceding rows had been entered into the regression equation. Entries in the second column indicate the increment in R^2 associated with the addition of the variable on the row into the regression equation. Finally, values in the third column indicate the F values for the significance either of the initial R^2 or of the increment in R^2. It was indicated that age was associated with 14.0% of the variance and WM with 5.1% when each was considered alone, but 15.7% of the variance was accounted for when age was entered into the equation after WM. The increment in R^2 associated with age after controlling WM is therefore 10.6%. Similarly, 9.5% of the variance was associated with the SMS measure alone, increasing to 15.2% when age was entered following SMS, and so on.

Table 3 Hierarchical Regression Results Based on the Measures of Performance from Working Memory, Sensorimotor Speed, and the Slope as Index of Subtraction Task-dependent Slowing

Criterion / predictor	R^2	Incr. R^2	F
Slope			
Age	0.140		25.94**
WM	0.051		8.63*
Age	0.157	0.106	19.73**
SMS	0.095		16.73**
Age	0.152	0.057	10.52**
SMS	0.095		16.73**
WM	0.114	0.019	3.13
Age	0.164	0.050	9.38*

Note. Incr. R^2 indicates that the increment in R^2 associated with adding the variable to the regression; the F value evaluates the statistical significance of R^2 for the first variable entered or the increment in R^2 associated with the addition of the second or third variable. WM = Working Memory; SMS = Sensorimotor speed. *: $p < 0.01$; **: $p < 0.001$.

The most interesting aspects of the data in Table 3 are the values of R^2 associated with age before controlling any of the other variables, and the values of R^2 for age after removing the variation associated with measures of WM and SMS. Overall, the attenuation of the age-related effects on slope measure of arithmetic was substantial after controlling measures of WM and SMS, and there is a larger attenuation of the age-related effects on slope after control of SMS than after control of WM (i.e., reductions in R^2 to 5.7% for SMS vs. 10.6% for WM). By expressing the final measure as a percentage of the original measure, 24.3% (i.e., [0.140 − 0.106]/0.140 × 100 = 24.3%) of the age-related differences in slope were attenuated by controlling the variance associated with the WM measure, whereas 59.3% (i.e., [0.140 − 0.057]/0.140 × 100 = 59.3%) of the age-related differences in slope were attenuated by controlling the variance associated with the SMS measure. However, 35.7% (i.e., [0.050/0.140] = 0.357, and 0.357 × 100 = 35.7%) of the total age-related effects on slope measure of mental subtraction were not mediated by age-related reductions in WM and/or SMS.

3 Discussion

The results of this study provided clear evidence of age-related decline in mental subtraction and the potential mediating role of WM and SMS. We observed that RT and errors increased with increasing age and arithmetic task difficulty, and the significant age × task difficulty interaction in RT measure of subtraction. Moreover, the magnitude of age differences in mental subtraction was reduced significantly by statistically controlling measures of WM and SMS. It was noteworthy that there was a larger attenuation of the age-related effect on mental subtraction after control of SMS than after control of WM. In other words, the influence of WM was considerably weaker than that of SMS. However, nearly 40% of the total age-related variance in RT measure, and 65% of the total age-related variance in accuracy measure of mental subtraction were not accounted for by age-related reductions in WM and SMS.

Comparing to the result of Geary et al.[8], the subtraction task in our study was much more difficult. Specifically, Geary et al.[8] studied processing speed differences of simple and complex mental subtraction in younger and older adults, in which the simple subtraction consisted of a single-digit minuend and subtrahend that produced a positive difference (e.g., 8 − 3), while complex subtraction problem consisted of a double-digit minuend and a single-digit subtrahend (e.g., 87 − 9). Geary et al.[8] found that older adults were slower at number encoding and number production but faster at executing the borrowing procedure in complex subtraction than younger adults, and younger adults didn't show an advantage for overall solution time in complex subtraction. This result may be overestimated because older subjects showed significant advantage in years of education in their study. Despite of this, the findings in the studies of Geary et al. [8] are basically consistent with the finding for addition [4], multiplication [7, 10] and subtraction [9]. All of their studies indicated that older adults might have a higher skill for basic fact retrieval (central processing) in mental arithmetic than do young adults, although the young group showed an advantage for overall solution times. The dissociation between the central and peripheral processes indicated age-related slowing of mental arithmetic was task or process-specific.

In our study, we conducted both aggregated (i. e., general linear model) and individual data analyses, and found that results from the two analytical approaches were in agreement, and consistent with Allen et al. [7, 10], Geary et al. [8], Geary & Lin [9], and Geary & Wiley [4]. First, the reliable age × task difficulty interaction in RT measures indicated that age-related decline of mental subtraction was differential and task or process-specific. Second, general linear model and individual data analyses revealed that the magnitude of age differences in mental subtraction was reduced significantly with the age differences in WM and SMS partialled out. However, age-related slowing of mental subtraction processing wasn't fully explained by age-related reduction of WM and SMS. In other words, significant unique affect of age on RT and accuracy measures of mental subtraction wasn't shared completely. It was indicated that there wasn't a common factor mediated age difference in mental subtraction, consistent with the reevaluation of Anstey, Luszcz, & Sanchez [25] on the common factor theory. Anstey, Luszcz, & Sanchez [25] found that speed did not fully mediate the effect of age or sensory function (e. g., visual acuity and audiometry) on cognition. At this point, the findings in our study are not consistent with Salthouse & Coon [6].

It was noteworthy that the results of this study, consistent with other studies found in the United States samples [4, 7-10], were found in the China sample. At least, the results of current study indicated that the cross-national difference in mental subtraction between China and the United States samples may be small, although Geary, Salthouse, Chen, et al. [26] showed a different pattern of cohort effects in the United States and China. Geary et al. [26] found that, for the arithmetic tests, the younger Chinese outperformed the older Chinese adults, but the groups of younger and older American adults had comparable arithmetical abilities. Furthermore, Geary, Hamson, Chen, et al. [27] showed a cross-generational decline in arithmetical abilities in the United States and a cross-generational improvement in China. In our study, however, so much of the unexplained variance was not completely attributed to educational/cohort effect, because the young and older samples were roughly equal in years of education. In our opinion, our data reflected more about the actual aging process.

In summary, this study provided some interesting results on the role of WM and SMS in age differences in mental subtraction. We found that RT and errors increased with increasing of age and arithmetic task difficulty, but the magnitude of age differences in mental subtraction was reduced by statistically controlling measures of WM and SMS. Moreover, there was a larger attenuation of the age-related effect on mental subtraction after control of SMS than after control of WM. However, WM and SMS didn't fully mediate the effect of age on mental subtraction. The developmental changes in mental subtraction during childhood and adolescence and the potential mediating role of WM and SMS seem to be unclear yet. On the other hand, at the neurobiological level, the exact mechanisms of age differences in performance on mental arithmetic tasks are yet to be elucidated. Future research seems to investigate the developmental pattern of mental subtraction during childhood and adolescence, and the neuroanatomical correlates of age-related variance in mental arithmetic processing.

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References

1 Ashcraft M H. Cognitive arithmetic: A review of data and theory. Cognition, 1992, 44: 75 ~ 106

2 Zbrodoff N J. Why is 9 + 7 harder than 2 + 3? Strength and interference as explanations of the problem - size effect. Memory & Cognition, 1995, 23: 689 ~ 700

3 Charness N, Campbell J I D. Acquiring skill at mental calculation in adulthood: A task decomposition. Journal of Experimental Psychology: General, 1988, 117: 115 ~ 129

4 Geary D C, Wiley J G. Cognitive addition: Strategy choice and speed - of - processing differences in young and elderly adults. Psychology and Aging, 1991, 6: 474 ~ 483

5 Liu C, Li D, Li G. On mental arithmetic with increasing age and its mechanism (in Chinese). Acta Psychologica Sinica, 1999, 31: 306 ~ 312
(**刘昌, 李德明, 李贵芸. 心算加工年老化及其机制研究. 心理学报**, 1999, 31: 306 ~ 312)

6 Salthouse T A, Coon V E. Interpretation of differential deficits: The case of aging and mental arithmetic. Journal of Experimental Psychology: Learning, Memory and Cognition, 1994, 20: 1172 ~ 1182

7 Allen P A, Ashcraft M H, Weber T A. On mental multiplication and age. Psychology and Aging, 1992, 7: 536 ~ 545

8 Geary D C, Frensch P A, Wiley J G. Simple and complex mental subtraction: Strategy choice and speed - of - processing differences in younger and elderly adults. Psychology and Aging, 1993, 8: 242 ~ 256

9 Geary D C, Lin J. Numerical cognition: age-related differences in the speed of executing biologically primary and biologically secondary processes. Experimental Aging Research, 1998, 24: 101 ~ 137

10 Allen P A, Smith A F, Jerge K A, et al. Age differences in mental multiplication: Evidence for peripheral but not central decrements. Journal of Gerontology: Psychological sciences, 1997, 52B: P81 ~ P90

11 Cerella J. Information processing rates in the elderly. Psychological Bulletin, 1985, 98: 67 ~ 83

12 Cerella J. Age effects may be global, not local: Comment on Fisk and Rogers (1991). Journal of Experimental Psychology: General, 1991, 120: 215 ~ 223

13 Ashcraft M H. Cognitive psychology and simple arithmetic: A review and summary of new directions. Mathematical Cognition, 1995, 1: 3 ~ 34

14 Salthouse T A. Speed mediation of adult age differences in cognition. Developmental Psychology, 1993, 29: 722 ~ 738

15 Salthouse T A. The aging of working memory. Neuropsychology, 1994, 8: 535 ~ 543

16 Salthouse T A. The processing - speed theory of adult age differences in cognition. Psychological Review, 1996, 103: 403 ~ 428

17 Baddeley A D. Working memory. Science, 1992, 255: 556 ~ 559

18 F rst A J, Hitch G. Separate roles for executive and phonological components of working memory in mental arithmetic. Memory & Cognition, 2000, 28: 774 ~ 782

19 Logie R H, Gilhooly K J, Wynn V. Counting on working memory in arithmetic problem solving. Memory & Cognition, 1994, 22: 395 ~ 410

20 No l M, D sert M, Aubrun A, et al. Involvement of short - term memory in complex mental calculation. Memory & Cognition, 2001, 29: 34 ~ 42

21 Adams J W, Hitch G J. Working memory and children's mental addition. Journal of Experimental Child Psychology, 1997, 67: 21 ~ 38

22 Jonides J. Working memory and thinking. In: Smith E E, Osherson D ed. Invitation to cognitive science: Thinking (Vol. 3, 2nd ed.). Cambridge: MIT Press, 1995. 215 ~ 265

23 Kail R. Developmental change in speed of processing during childhood and adolescence. Psychological Bulletin, 1991, 109: 490 ~ 501

24 Kail R. Speed of information processing: Developmental change and links to intelligence. Journal of School Psychology, 2000, 38: 51 ~ 61

25 Anstey K J, Luszcz M A, Sanchez L. A Reevaluation of the common factor theory of shared variance among age, sensory function, and cognitive function in older adults. Journal of Gerontology: Psychological sciences, 2001, 56B: P3 ~ P11

26 Geary D C, Salthouse T A, Chen G, et al. Are east Asian versus American differences in arithmetical ability a recent phenomenon? Developmental Psychology, 1996, 32: 254 ~ 262

27 Geary D C, Hamson C O, Chen G, et al. Computational and reasoning abilities in arithmetic: Cross - generational change in China and the United States. Psychonomic Bulletin & Review, 1997, 4: 425 ~ 430

工作记忆和感觉运动速度在心算加工年老化过程中的作用

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摘　要

对心算加工年老化研究有助于阐明认知老化规律,然而有关心算老化的少量研究结果仍存在不一致甚至矛盾之处。导致这种不一致的原因十分复杂,表面上看,不同认知老化研究所采用的统计方法不尽相同导致了结果的歧异。例如,在心算的年老化研究中,有的研究结论基于群体的数据分析,如层级回归分析(hierarchical regression analyses)或方差分析,如 Salthouse 和 Coon(1994);另有一些研究先对每一个体数据作线性回归分析,如此得到斜率和截距(分别表示心算的中枢加工时间和外周感觉运动时间),然后再行层级回归分析或方差分析,如 Allen 等(1992,1997)。这两类统计分析所得的结果很不一致。从理论上看,只要所采用的统计方法是合理的,统计方法的不尽相同应不会导致矛盾。但在实际情况下,统计分析误差增加了结论不一致的可能性,从而增大了揭示心算老化复杂性规律的难度。事实上,心算活动的年龄差异可能来自于记忆、加工速度等不同认知资源的老化差异。为了深入探讨这一问题,我们进一步研究了工作记忆和感觉运动速度在心算加工年老化过程中的作用。

被试共 161 人,20 ~ 79 岁,身体健康,受教育年限 12 年以上,以 10 岁段划分为 6 个年龄组,组间文化程度基本匹配。被试任务包括:(1) 连续减法心算,分别为 1000 - 3、1000 - 7、1000 - 13 及 1000 - 17 等 4 种,在排除了被试看屏幕和按键的感觉运动时间后得到心算所需的时间;(2) 数字计算工作记忆,根据工作记忆对信息同时进行加工和储存的特点,要求被试计算完题后再回忆答案,以获得工作记忆广度指标;(3)“数字复制”(digit copying),以获得感觉运动速度指标。实验在 386 微机上进行。对所得数据分别进行了上述群体数据与个体数据分析。两种数据分析方法得到了相同的结果,一致表明,在控制工作记忆与感觉运动速度的年龄差异后,心算活动的年龄差异显著降低。而且,控制感觉运动速度的年龄差异后心算活动年龄差异的降低程度要大于控制工作记忆的年龄差异后心算活动年龄差异的降低程度。这说明,感觉运动速度在心算加工年老化过程中发挥了更大作用。但是,工作记忆与感觉运动速度二者的年龄差异并不能完全解释心算活动的年龄差异,表明心算加工的年老化存在其特殊性过程,不支持认知老化的普遍减慢假说(generalized slowing hypothesis)。

关键词　工作记忆,感觉运动速度,年老化,心算。

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