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Speed of Accessing Arithmetic Facts in Long-Term Memory: A Comparison of Chinese-American and Anglo-American Children

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Chinese-American (CA) and Anglo-American (AA) children in grades 4 to 6 were compared on a nonverbal test of intelligence (Raven's Standard Progressive Matrices) and 12 chronometric variables, which measure the speed and consistency of retrieval of well-learned simple arithmetic facts (i.e., addition, subtraction, and multiplication of single digits) from long-term memory (LTM). Despite their extreme simplicity, these chronometric variables are correlated with psychometric intelligence. In this study, the CA and AA groups differed significantly on these chronometric variables, but the differences appear to be multidimensional and cannot be attributed simply to the groups' difference in psychometric intelligence, or *g*. The results are consistent with the hypothesis that accessing elementary arithmetic knowledge in LTM is a more completely automatized process in the CA than in the AA pupils. © 1994 Academic Press, Inc.

While solving a problem, subjects must often draw upon prior learned items of information. Attempts to explain the causes of individual differences in mathematics achievement in terms of cognitive theories of information processing have hypothesized essentially that individual differences in the speed with which the information retrieval process occurs may be reflected in individual differences in the ease of learning more advanced forms of arithmetic and in the facility of performance on complex problems in which some of the crucial elements for solution are relatively elementary items of information stored in LTM (e.g., Ashcraft, 1982; Kaye, 1986; Kaye, Post, Hall, & Dineen, 1986). The more the retrieval process has become automatic through practice, the faster it occurs and the more it accrues the additional advantages of automatic processing, as contrasted with controlled processing. The theory of controlled and automatic processing of information (Schneider & Shiffrin, 1977) is highly germane to any theories of intellectual achievement.

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Briefly, *controlled processing* demands focused attention, conscious mental effort, is relatively slow, and deals with information input serially, being able to deal with only a very limited amount of information at one time and being unable to execute different operations simultaneously. A large input demand on controlled processing over-crowds the capacity of working memory, resulting in a "breakdown" in processing. Solving novel problems, learning new knowledge or skills, and consciously monitoring an unpredictably changing situation that calls for varied responses all involve controlled processing. In contrast, *automatic processing* does not demand the person's full attention, it is relatively effortless, it can deal with relatively large amounts of information and perform operations on it simultaneously, and, most importantly for the present context, when certain information processes have become automatic, they do not impinge on the limited capacity of working memory, leaving it free for controlled processing of other information, such as the variable or novel aspects of problems, which cannot be automatized.

Considerable attention has been paid in recent years to the relatively outstanding levels of achievement of Asian students in mathematics and other quantitative fields (e.g., Lynn, 1988; Stevenson, Lee, & Stigler, 1986). Differences in performance between the math achievement levels of American and Asian students appear as early as kindergarten and continue throughout the elementary school years. Various factors have been suggested to explain the striking differences in performance, but attempts to understand the mathematical ability of Asians have focused on differences in educational and socio-cultural background and values to the near exclusion of intellectual or cognitive (e.g., Stevenson, Chen, & Lee, 1993). Factors put forth as important include the central localization of educational policy, the greater amount of time spent in school, the greater amount of time spent on mathematics instruction, valuing hard work over innate ability, demanding and expecting achievement and upward mobility, inducing guilt about parental sacrifices, stressing the need to fulfill obligations, instilling respect for education and teachers, and making social comparisons with other Asian-American families in terms of educational successes (Sue & Okazaki, 1990).

More recently, however, differences in mathematics achievement between Chinese school children (in China) and American children of European ancestry (in the United States) have been interpreted in terms of the Chinese pupils' advantage in the speed of information processing, specifically the speed of retrieval of numerical information from memory (Geary, Fan, & Bow-Thomas, 1992). (These authors also provide an excellent review of the most relevant recent studies in this vein.) Although the study by Geary *et al.* (1992) contrasted Chinese pupils in China with pupils of European ancestry in the United States (henceforth referred to as "Anglo-American"), thereby implicating possibly crucial differences in the educational programs of the contrasted groups, differences in mathematics achievement have also been noted between Asian (i.e., Chinese and Japanese) and European-ancestry groups attending school within the United States, even when exposed to the same math curriculum, methods of instruction, and the like (Mullis, Dossey, Owen, & Phillips, 1991; for reviews: Chan & Vernon, 1988; Flynn, 1991; Lynn, 1988; Vernon, Jackson, & Messick, 1988).

The present study is aimed at determining whether Anglo-American and Chinese-American pupils within the same school system in Northern California differ in speed and consistency of retrieving relatively simple items of well-learned information from LTM. The investigation is limited to a narrow class of information, namely, elementary number facts that were common knowledge to all of the participants in the study, as assessed by a nonspeeded paper-and-pencil test. The findings cannot be generalized beyond this particular class of information, of course, because no attempt has been made to demonstrate a broad factor of speed of information retrieval that is common to a wide variety of information content, although such a factor might well exist.

METHOD

Subjects

The subjects were elementary public school pupils in regular education classes in approximately equal numbers from Grades 4 through 6 in Bay Area schools. The Anglo-American (AA) sample ($N = 73$) was obtained in a predominantly middle-class suburban school; the Chinese-American (CA) sample ($N = 155$) was obtained from a public school located in the comparatively less affluent "Chinatown" section of the city.[1] The percentages of males and females (M%/F%) were 48%/52% for CA and 49%/51% for AA. The very unequal *N*s in the two groups were not by design but resulted from time constraints in scheduling pupils for individual testing. The only planned basis for selection of subjects from the total pool of pupils available was a brief screening test for knowledge of elementary number facts (see below).

Mean ages of the AA and CA groups were 10.8 (*SD* 1.0) and 10.4 (*SD* 1.0) years, respectively.

Chronometric Techniques and Procedures

Because the chronometric tasks were intended to measure individual differences in information processing speed rather than in knowledge per se, the basis for selecting subjects was having a perfect score on a short, nonspeeded written test of elementary number facts (i.e., simple addition, subtraction, and multiplication of single digits). Pupils have typically learned these facts before entering the 4th grade. The chronometric tasks consisted of the

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[1] The countries of birth of the 155 subjects in the CA sample and their numbers are as follows: United States (43), China (64), Hong Kong (13), Vietnam (28), Taiwan, Malaysia, and other Pacific Rim countries (7).

same number facts as the written test and were intended only to measure the speed of retrieval and verification of this information from long-term memory.

Chronometric Apparatus. The subject's binary response console, shown in Fig. 1, consists of a 17-cm × 26-cm panel of three pushbuttons (2.6-cm diameter) spaced equidistantly (6.5 cm) apart. Forming a triangle, the black "home" button was nearest to the subject, with the two green binary response buttons above. The console was interfaced with an IBM-PCXT computer, which controlled the presentation of stimuli and recorded the subject's response times and errors. The problems were presented on an IBM monochrome monitor located directly behind the subject's response console.

The *Math Verification Test* (*MVT*) consists of single-digit *addition, subtraction,* and *multiplication* problems, presented on the monitor in the form A * B = C, where A and B are digits 1 through 9 and * is either +, −, or ×. On a random half of the trials C is the *correct* answer and on the other trials it is an incorrect answer. Three types of incorrect answers were programmed: (1) the correct answer ± 1 (e.g., 2 + 4 = 7); (2) the correct answer for a different type of computation (e.g., 2 + 4 = 8); and (3) a figure much larger or smaller than the correct answer (e.g., 3 + 5 = 35). The larger digit in each addition and multiplication equation appeared first or second on alternate trials. In the subtraction problems the larger digit was consistently the minuend.

Subjects first responded to fifteen practice trials, evenly divided between the three types of problems. Then separate blocks of addition, subtraction, and multiplication problems were presented, in that order, with 20 trials in each block. Each set of problems was prefaced by a title, thus informing the subject of the type of upcoming problems. All trials were subject-paced. One second after the subject pressed the home button, a square appeared in the center of the screen. This preparatory stimulus oriented the subject's eyes to the location of the mathematical sign (+, −, or ×) of the upcoming problem. After a random interval of 1 to 4 s, the problem appeared on the screen. The subject's task was to verify the correctness of the answer provided by pressing the appropriate button, which was designated either "yes" or "no." Correct responses were immediately followed by the word

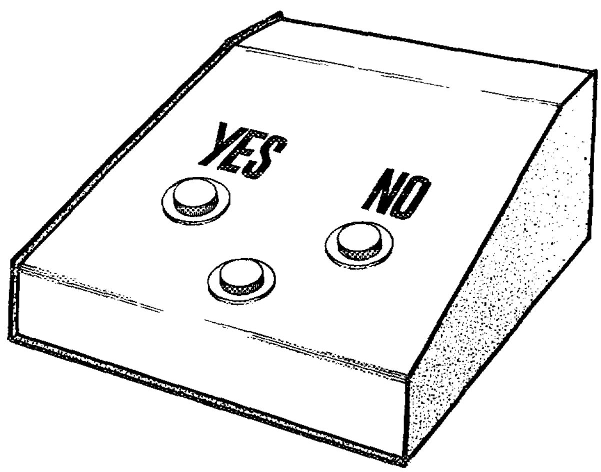

FIG. 1. Binary response console used in the Math Verification Test (MVT). The lower button in the equilateral "triangle" formed by the 3 pushbuttons is the "home" button; the response buttons are labeled YES and NO. The reaction stimuli (i.e., math problems) are presented on an IBM-PC monitor placed behind the response console.

Correct and a 1-s "beep"; incorrect responses were followed only by the word **Incorrect**. Every subject obtained the same number of errorless trials, because trials with incorrect responses were repeated at the end of each set.

Chronometric variables from the MVT. Four different variables were obtained from only the 20 error-free test trials on each MVT task:

Reaction time (RT) is the interval (in ms) between onset of the stimulus and the subject's lifting his/her finger from the home button. (Measured as *median* RT over 20 trials).

Movement time (MT) is the interval between lifting the finger from the home button and pressing the lighted stimulus button, a movement of 6.5 cm. (Measured as the *median* MT over 20 trials).

Standard Deviation of RT (RT*SD*) is a measure of intraindividual variability in RT, that is, the variability of the subject's RT from trial-to-trial, calculated as the standard deviation (*SD*) of the subject's RTs over 20 trials. RT*SD* has been found in previous studies to be even more highly correlated with psychometric *g* than is RT per se. The nature and importance of RT*SD* as a variable in information processing have been explicated in detail elsewhere (Jensen, 1992).

Standard Deviation of Movement Time (MT*SD*) is analogous to RT*SD*, as a measure of intraindividual variability in MT.

Total Errors is the number of incorrect responses (i.e., wrong button presses) plus the number of trials on which RT < 170 ms or > 2000 ms. These outlier RTs are considered flukes for normal children in Grades 4 to 6, and so the problems on which they occurred were recycled at the end of the series of trials. Hence every subject's median RT was based on the same number of correct test trials with RTs between 170 and 2000 ms.

Psychometric Tests

Standard progressive matrices (SPM). Raven's SPM is a 60-item multiple-choice nonverbal paper-and-pencil test of reasoning based on figural materials. It is highly loaded on psychometric *g*, the general factor common to many tests of "intelligence." It was administered to intact classes, with a 45-min time limit.

Mathematics achievement test (MAT). The MAT is a composite battery consisting of the mathematical concepts, applications, and computation skills that are included in the school's math curriculum through Grade 6. Only the CA group received this test, which was used here to examine a specific hypothesis about the relationships among g, math achievement, and speed of accessing elementary arithmetic facts in LTM.

RESULTS

Linear, quadratic, and cubic components of age were regressed out of all of the test scores and chronometric data in the combined samples prior to all of the following analyses. All the statistics reported henceforth are age-adjusted.

Standard Progressive Matrices

The mean scores on Raven's SPM were 38.6 (SD = 8.9) for AA and 41.4 (SD = 8.5) for CA. This difference, equivalent to 0.32 SD units or about 5 IQ points, is highly significant (t = 4.91, p < .001).

Errors in MVT

Differences in mean response errors between the Addition, Subtraction, and Multiplication tasks of the MVT are extremely slight and nonsignificant. The overall mean errors on each task is 2.65. The overall mean errors in the CA and AA groups differ by only 0.17, which is completely nonsignificant ($p > .50$).

Chronometric Variables in the MVT

Table 1 shows the means and *SD*s of the MVT variables for CA and AA and the AA-CA difference in *SD* units. CA have significantly faster RTs and significantly slower MTs than AA. CA also have *lower* intraindividual variability (RT*SD*) than AA.

Note the significant differences between AA and CA on MT (faster for AA), even though MT has nonsignificant and near-zero correlations with *SPM* in both groups. Some factor other than *g* is the basis of the group differences in MT. Because the AA-CA difference is consistently *positive* for RT and consistently *negative* for MT, one may ask if this difference between groups is due to CA's dividing the total processing time between RT and MT, trading-off one against the other. This strategy would imply that subjects who have faster RTs would also have slower MTs, and vice versa, thereby creating a *negative* correlation between RT and MT. And this is what we find. The correlations between RT and MT on the Addition, Subtraction, and Multiplication tasks are, respectively, −.56, −.47, and −.41 in the CA group and −.36, −.39, and −.36 in the AA group, suggesting the presence of the hypothesized strategy in *both* groups. The slightly larger correlations in the CA, however, would hardly be sufficient

TABLE 1
MEAN AND *SD* (IN MS) OF THE MATH VERIFICATION TEST VARIABLES IN THE CHINESE-AMERICAN (CA) AND ANGLO-AMERICAN (AA) SAMPLES AND THE AA-CA DIFFERENCES IN *SD* UNITS

	Chinese-Amer.		Anglo-Amer.		
Variable	Mean	*SD*	Mean	*SD*	AA-CA difference
Add RT	1199	585	1531	889	.47***
Add MT	601	368	446	274	−.45***
Add RT*SD*	485	359	735	815	.46***
Add MT*SD*	289	124	290	142	.00
Sub RT	1166	589	1479	888	.45***
Sub MT	562	350	444	303	−.35***
Sub RT*SD*	485	587	670	1071	.24***
Sub MT*SD*	266	126	278	126	.09
Mult RT	1249	797	1429	691	.23**
Mult MT	524	328	400	266	−.40***
Mult RT*SD*	475	456	567	630	.18**
Mult MT*SD*	251	127	246	126	−.04

*,**,*** Significant at the 5, 1, and 0.1% levels (2-tailed), respectively.

to explain the complete reversal of the direction of the AA-CA mean difference on RT and MT. Moreover, we note that, despite the CA's having longer MT than AA, the CA's total response time (i.e., RT + MT) is still shorter (by an average of 143 ms) than the AA's. So it is quite implausible that the faster RT of the CA could be explained simply in terms of their adopting a RT/MT trade-off strategy to a greater degree than AA.

Table 2 shows the Pearson correlation coefficients between each of the MVT variables and Raven's SPM in each group, and also the mean *r*s. The pattern of correlations across the two groups appears fairly similar, the *r* between the two column vectors being +.77. There is a conspicuous contrast between RT and MT in their correlations with the SPM. The RT correlations are consistently significant, while the MT correlations are consistently nonsignificant. The overall mean *r* for all the RT and RT*SD* variables is −.25 ($p < .001$); for all the MT and MT*SD* variables the mean *r* is +.01.

Is there a relationship between (*a*) the column vector of correlations between the 12 MVT variables and the SPM (i.e., the columns in Table 2) and (*b*) the column vector of AA-CA standardized mean differences on the MVT variables (i.e., the last column in Table 1)? The Pearson correlation (*r*) and rank order correlation (r_s) between these two vectors (*a* and *b*) are: $r = -.82$ and $r_s = -.77$ for the CA vector of correlations; $r = -.91$ and $r_s = -.94$ for the AA vector; and $r = -.93$ and $r_s = -.90$ for

TABLE 2
CORRELATIONS OF MATH VERIFICATION TEST VARIABLES WITH STANDARD PROGRESSIVE MATRICES IN CHINESE-AMERICAN AND ANGLO-AMERICAN CHILDREN (DECIMAL POINTS OMITTED)

	Correlation with progressive matrices		
Variable	Chinese-Amer.	Anglo-Amer.	Mean (*r*)
Add RT	−210**	−314**	−262***
Add MT	−032	063	015
Add RT*SD*	−208**	−247**	−227***
Add MT*SD*	−089	011	−039
Sub RT	−250**	−310**	−280***
Sub MT	034	095	065
Sub RT*SD*	−346***	−184	−265***
Sub MT*SD*	−143	−170	−107
Mult RT	−249**	−234*	−241***
Mult MT	057	219	138
Mult RT*SD*	−326***	−095	−210**
Mult MT*SD*	−135	145	005

*,**,*** Significant at the 5, 1, and 0.1% levels (2-tailed), respectively.

the vector of mean correlations. All of these correlations are significant ($p < .01$). They indicate that the larger the chronometric variable's correlation with the SPM, the faster is the CA's response compared to the AA's. Because the SPM is generally considered a good measure of psychometric g, this finding suggests that the degree of AA-CA difference on the MVT variables is highly related to the MVT variables' g loadings.

MVT and Mathematics Ability

Because the standardized AA-CA differences on the MVT (Table 1) are much larger than one would predict on the basis of the SPM difference of 0.32 *SD* units between the groups, and given the fact that the correlations between the MVT variables and the SPM are rather small (the overall mean r for RT and RT*SD* is $-.25$), the question arises as to what extent mathematical aptitude and knowledge are correlated with the MVT. Are the correlations between MVT and math ability appreciably greater or different in any way from the MVT's correlations with the SPM?

This was examined only in the CA group. Total scores on a comprehensive test of math achievement (MAT) were correlated with the SPM ($r = +.59$) and with each of the MVT variables, shown in Table 3 as the first column vector of correlations [headed r(MAT)]. This vector closely resembles the vector of correlations of the SPM with the MVT variables (first column of Table 2). The correlation between the two vectors is $+.93$. The fact that the MAT is correlated only $+.59$ with the SPM, however, means that the MAT measures something besides g (or whatever is measured by the SPM), most probably a numerical ability factor and the degree of over-learning and automatization of elementary number facts. But it also appears that the MVT variables are mainly correlated with the g portion of the MAT's total variance.

To find out if the MAT adds an appreciable increment over the SPM in the prediction of the MVT variables, we computed the multiple correlation (R) of MAT and SPM with each of the MVT variables, shown in Table 3.

The mean R over just the RT and RT*SD* variables is $-.34$, as compared with the corresponding correlations of $-.26$ for the SPM alone and $-.32$ for MAT alone. So it appears that some factor in the MAT, that is independent of SPM, adds to the prediction of MVT. The correlation of MAT with MVT when SPM is regressed out of both variables is provided by the partial correlation (PC) between MAT and MVT, shown in Table 3. The mean PC for the RT and RT*SD* variables is reduced to $-.21$, as compared with the zero-order $r = -.32$ between MAT and MVT. (A partial $r > .21$ is significant at $p < .01$.)

Hence we must conclude that some factor(s) involved in math ability,

TABLE 3
CHINESE-AMERICAN DATA ONLY

Variable	r(MAT)	R^{ab}	PC	SPC-a	SPC-b
Add RT	−310*	−312***	−235**	−231**	−032
Add MT	−036	−038	−021	−021	−013
Add RT*SD*	−300**	−302***	−224**	−219**	−037
Add MT*SD*	−031	−093	+027	−027	−088
Sub RT	−301**	−314***	−196*	−190*	−089
Sub MT	−050	−094	−087	−088	+079
Sub RT*SD*	−386***	−412***	−239**	−224**	−145
Sub MT*SD*	−134	−155	−062	−061	−079
Mult RT	−290**	−305***	−182*	−176*	−095
Mult MT	−061	−131	−118	−118	+116
Mult RT*SD*	−348	−378***	−203*	−191*	−148
Mult MT*SD*	−193*	−195*	−141	−140	−025

[a] r(MAT) = correlation between MVT variable and math achievement (MAT); *R* = multiple correlation [i.e., prediction of MVT variable jointly by Standard Progressive Matrices (SPM) and MAT]; PC = partial correlation between MVT variable and MAT (i.e., correlation between MVT and MAT with influence of SPM removed from both MVT and MAT); SPC-a = semi-partial correlation between MVT and MAT (i.e., correlation between MVT and MAT with influence of SPM removed only from MAT); SPC-b = semi-partial correlation between MVT and SPM (i.e., correlation between MVT and SPM with influence of MAT removed only from SPM). (Decimal points omitted from correlations.)

[b] A multiple *R* is usually not signed, but it is given a negative sign here to indicate that lower values of the chronometric variables are associated with higher scores on the SPM and MAT.

*,**,*** Significant at the 5, 1, and 0.1% levels (2-tailed), respectively.

independently of *g* as measured by the SPM, is significantly correlated with RT and RT*SD* variables of the MVT when both of these variables are stripped of *g*. We hypothesize that this residual non-*g* factor, which is common to MAT and MVT, reflects individual differences in the automatization of simple number facts through practice, which increases the speed of access to this information in LTM.

We can conceive of the MAT in terms of orthogonal factors that measure *g* + speed of access to numerical information, while the SPM measures only *g*. Both of these factors are reflected in the MVT. Given this model, we should predict that the semi-partial correlations (also referred to in statistics as "part-correlation") between MAT and the MVT variables (SPC-a in Table 3), with SPM regressed out of only MAT (leaving MVT wholly intact) will be essentially the same as the full partial correlations (i.e., PC in Table 3). However, since *g* is contained in the variance of MAT, the semi-partial correlations between SPM and the MVT variables (column SPC-b in Table 3) with MAT regressed out of only SPM (leaving MVT wholly intact) should be reduced to near-zero. These effects are clearly seen in the semi-partial correlations shown in the last two columns of Table 3. The mean of the semi-partial correlations for just the RT and RT*SD* variables when SPM is removed (i.e., column SPC-a in Table 3) is $-.21$, which is the same as the full partial correlation (PC). But the corresponding semi-partial correlations when MAT is removed (column SPC-b in Table 3) average only $-.09$, and none even approaches significance.

Thus it is evident that performance on the MVT reflects *g* plus some numerical ability factor that is independent of *g*. This factor is probably the automatization of simple arithmetic knowledge, as evinced by quick access to number facts in LTM. Just how much of the mean AA-CA difference on the MVT variables, particularly RT and RT*SD*, is associated with a group difference in *g* and how much is associated with a difference in the degree of automatization of number facts is not answered by this study. That both factors are probably involved in the AA-CA differences on the MVT, however, is implied by the fact that the differences in RT are larger (averaging $+.39$ *SD*) than the difference on the SPM ($-.32$ *SD*).

DISCUSSION AND CONCLUSIONS

The CAs significantly exceeded AAs in the speed of accessing elementary arithmetic facts in LTM. Although the CAs had slightly higher scores (equivalent to about 5 IQ points) than AAs on the SPM, this difference cannot possibly account for the even larger AA-CA difference in speed of response (RT) and in its trial-to-trial consistency (RT*SD*) on the Math Verification Test (MVT). Some other factor(s) besides *g* or whatever is measured by the SPM has to be involved in the AA-CA difference.

Differences in general motivation in the test situation seems an unlikely factor, given that the group differences are in *opposite* directions on the RT and MT variables. The CAs were faster than AAs in RT, but slower than AAs in MT. It is hard to imagine that a group difference in motivational state would speed up RT and slow down MT in one group and have the opposite effects in the other. Also, the CAs are consistently faster than AAs only on those chronometric variables (RT and RT*SD*) that are significantly correlated with psychometric *g* (i.e., the SPM) and with math achievement (MAT). The motor aspects (MT and MT*SD*) of the MVT were not significantly correlated with either SPM or MAT.

The greater speed of the information retrieval process in the CAs could have any one or a combination of several probable causes: (1) It could reflect a generally faster speed of access to information in LTM, whatever the type of information; or (2) a special aptitude for dealing with numerical problems, or (3) a greater amount of practice on the number facts. A general difference in simple reaction time (SRT) per se seems an unlikely explanation for the present results, in view of the fact that a study of CA-AA differences (with *N*s of 585 AA and 167 CA, including all of the subjects in the present study) in various types of RT, that did not involve any informational content or retrieval of information from either STM or LTM, showed only a small and nonsignificant overall difference for RT (Jensen & Whang, 1993). However, when simple RT, which involves both sensory and motor factors, is subtracted from choice RT and discrimination RT, the CA group showed quite markedly and very significantly faster processing speed than the AA group. So a general factor of speed of information processing that is correlated with psychometric *g* and in which the CA exceed the AA, on average, cannot be ruled out in explaining, at least in part, the present results.

However, extensive practice is known to facilitate recall and also to increase the automatization of arithmetic operations (e.g., Geary *et al.*, 1992; Jensen, 1989, 1990). The tendency for practice to automatize cognitive skills may be positively related to *g*, but a large source of variance associated with differences in the amount of practice on particular skills may remain. The fact that the AA-CA difference in RT on the MVT is greater than would be predicted from the group difference in *g* (as assessed by the SPM) indicates that some factor in addition to *g*, we suspect most probably different amounts of practice in arithmetic computation, is responsible. This advantage of automatization and speedy access to learned basic arithmetic facts while children are in elementary school is probably an important factor, over and above *g*, in later success in learning at the more advanced levels of mathematics, and it may account, at least in part, for Asian students' notable success in quantitative fields of study. It is an hypothesis of sufficient educational import to be worthy of further investigation.

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