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Differential Enhancement of Working Memory With Mathematical Versus Verbal Precocity

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Two experiments compared the working-memory performance of highly gifted 13- and 14-year-olds who showed (a) both mathematical and verbal precocity, (b) primarily mathematical precocity, or (c) primarily verbal precocity. Experiment 1 examined (a) working-memory representational capacity for digit, letter, word, and location stimuli and (b) manipulation in working memory of digit, letter, and location stimuli. Verbally precocious youths showed enhanced capacity for words, and mathematically precocious youths showed enhanced capacity for digit and location stimuli. In working-memory manipulation, the mathematically precocious outperformed the verbally precocious with digits and letters. Experiment 2 examined speed of encoding into working memory. The verbally precocious showed enhanced encoding speed. Different types of intellectual talent appear to be associated with different working-memory characteristics and with differences in how digit and word stimuli are represented in memory.

Differences in intellectual ability have been associated with differences in memory span and speed of processing (Belmont & Butterfield, 1971; Cohn, Carlson, & Jensen, 1985; Dark & Benbow, 1990; Hunt, 1976, 1978; Hunt, Lunneborg, & Lewis, 1975; Keating & Bobbitt, 1978; Vernon, 1983), with variations in problem representation and "insight" (Chi, Glaser, & Rees, 1982; Sternberg & Davidson, 1983), with differences in accessible knowledge (Pellegrino & Glaser, 1982; Rabinowitz & Glaser, 1985), with development of automatic processing (Krutetskii, 1976) and tacit knowledge (Sternberg, 1986), with flexible and effective use of strategies (Campione, Brown, & Ferrara, 1982), and with differences in metacognitive skills (Brown, 1978; Sternberg, 1981). Despite the voluminous research on the nature of intelligence and superior intellect, relatively little is known about the processing characteristics of individuals at the upper end of the intelligence continuum, especially those whose superior intelligence is manifested in areas other than verbal (Jackson & Butterfield, 1986; Rabinowitz & Glaser, 1985).

Our research addressed this problem by examining the performance of intellectually precocious youth, young adolescents whose abilities were so advanced that they performed on the Scholastic Aptitude Test (SAT) at a level equal to or better than that of the typical college-bound senior; the youth were completing academic work at the college level in a summer program. The research examined performance on a variety of information-processing tasks as a function of talent. Specifically, we determined the extent to which verbally precocious youth could be differentiated from mathematically precocious youth in terms of performance on information-processing tasks.

From an information-processing perspective, differences in performance on a wide range of complex intellectual tasks, such as reasoning and reading comprehension, can be understood in terms of differences in basic cognitive processes that are measured by performance on very simple tasks (e.g., Cooper & Regan, 1982). Although details of models underlying this literature differ from study to study, there appears to be some consensus concerning at least two aspects of memory: (a) There is a distinction between a limited-capacity working memory (or short-term, or primary, memory) and long-term (or secondary) memory, and (b) long-term memory is accessed when information is encoded into working memory.

Our own research is conceptualized within a model that describes long-term memory and working memory as separate but related aspects of one memory system. They are related because the content of working memory is active, long-term memory representations (cf. Cowan, 1988; Hunt & Lansman, 1986; McClelland & Rumelhart, 1985; Shiffrin & Schneider, 1977). Working memory is the system in which information is temporarily held while being manipulated or transformed. Attention and conscious experience are associated with working memory. Long-term memory consists of highly interconnected units or representations.[1] The interconnections reflect knowledge and are the result of learning that has occurred from past interactions with the environment.

Working-memory encoding occurs when long-term-memory representations are fully activated, either by features in the environment or by activation from other units. Once encoded, or activated into working memory, the representations are subject to the control processes of working memory. The structure of long-term memory is such that representations of stimuli to which the system has been repeatedly

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[1] Although the discussion is written as if the units are individually meaningful, like Morton's (1970) logogens, this is just a semantic convenience. The same points apply to representations comprising patterns of units, like the distributed memory of McClelland and Rumelhart (1985).

exposed are more quickly encoded into working memory, are more easily maintained in an active state, and are more easily manipulated by control processes. We use the term compactness to capture these properties. In other words, familiar stimuli have more compact representations.

Furthermore, we conceptualize working memory according to the framework developed by Baddeley and colleagues (e.g., Baddeley, 1986; Baddeley & Hitch, 1974; Baddeley & Lieberman, 1980). In their model, working memory is divided into a central executive system that has access to two relatively independent buffer processes, the articulatory loop and the visuo-spatial sketchpad. Verbal representations, regardless of mode of input, are maintained by rehearsal processes comprising the articulatory loop, whereas nonverbal visual and spatial representations are maintained by processes comprising the sketchpad. Central executive processes act on all representations maintained in the buffers. Within this model, therefore, individual differences on working-memory tasks can result from differences in operations or differences in the representations on which operations are performed.

The literature suggests that performance on working-memory tasks is enhanced for high-ability students. For example, Cohen and Sandberg (1977) found that IQ scores correlated with measures of primary memory in young adolescents. Keating and Bobbitt (1978) showed that high-ability children exhibited more rapid memory scanning and were less affected by set size than average-ability students. Working within Baddeley's model, Dark and Benbow (1990) found that, relative to average-ability youth, mathematically and verbally precocious 13-year-olds were superior in both representing and manipulating (or operating on) information in working memory. Their level of performance was greater than that of average-ability peers and was comparable to that of college students.

Because mathematical and verbal precocity are distinct forms of giftedness (Benbow & Minor, 1990), however, Dark and Benbow also investigated differences between them. Although the capacity to represent information did not differ as much for mathematically and verbally precocious youth as did the ability to manipulate information in working memory, the mathematically precocious exhibited better performance in both. This finding was somewhat unexpected, because the literature had suggested that enhanced working memory was related to high verbal ability.

The identification of enhanced working memory with verbal ability in the literature (e.g., Ford & Keating, 1981; Hunt, Frost, & Lunneborg, 1973; Hunt et al., 1975) stems primarily from studies showing that students with high verbal ability have quicker access to semantic information in long-term memory. Borkowski and Peck (1986) reported that speed and/or efficiency in both encoding and decoding processes separated gifted from average-ability children. Hunt and colleagues (1973, 1975) showed that college students with high verbal scores on college entrance examinations were superior to those with low scores in accessing long-term memory and manipulating information in short-term memory. Similarly, Goldberg, Schwartz, and Stewart (1977) with college students and Ford and Keating (1981) with children found that high verbal ability related to efficiency of retrieval from long-term memory.

In most of these studies, however, mathematical ability was not fully addressed. It is possible, therefore, that the results reflect a confounding of verbal and mathematical ability. A second possibility is that verbal talent is associated with enhanced working-memory encoding rather than enhanced working-memory operations. The latter may be associated with mathematical talent. Thus, each talent might be associated with a distinct working-memory strength.

A third possibility is that the enhanced performance of the mathematically precocious youth in the results of Dark and Benbow (1990) was due to content-specific differences in stimulus representation rather than to general differences in the operation of the central executive. Because Dark and Benbow wanted to examine the characteristics of both the articulatory loop and the visuo-spatial sketchpad, they included both digit and spatial stimuli in their tasks. The spatial stimuli were locations in a 10-cell matrix. The literature had suggested that mathematical ability had a spatial or imagery component (Benbow, 1988; Burnett, Lane, & Dratt, 1979; McGee, 1979), so Dark and Benbow (1990) expected that the mathematically talented youth might show enhanced performance with the location items. Because the digit stimuli were merely named and not treated numerically, they expected no differences between the precocious groups with digits. The strongest performance differences favoring the mathematically precocious, however, were found when the task required manipulation of digit stimuli. Dark and Benbow suggested post hoc that digit stimuli may be in some sense more familiar to mathematically talented youth and, therefore, that representations of digits may be more compact and easier to manipulate. If this interpretation is correct, then verbally talented youth should perform better if letters are used as stimuli.

To test these possibilities, we examined the relationship between intellectual precocity and a variety of working-memory measures, using different types of stimuli. Specifically, we investigated (a) the accuracy with which information is maintained in working memory, (b) the accuracy with which information in working memory can be "manipulated" by associating it with other information in working memory, and (c) the speed with which information is activated from long-term memory into working memory. In each case we examined performance differences between differentially talented individuals to determine whether the two forms of precocity, mathematical and verbal, are associated with different patterns of cognitive abilities. For the first two questions, we also determined whether stimulus type interacted with talent to moderate performance.

Experiment 1

Experiment 1 investigated the two accuracy questions: Are there differences in working-memory representational capacity, effectiveness of operations, or both? The representational capacity of working memory is often measured by span tasks, particularly digit span (Dempster, 1981). In our theoretical conceptualization, span differences can result from either differences in general representational capacity or differences in the compactness of the long-term-memory representations that are activated into working memory. Dark and Benbow

(1990) reported enhanced performance in the mathematically talented with both a digit-span task, which in our conceptualization estimates the representational capacity of the articulatory loop, and a location-span task, which represents the capacity of the visuo-spatial sketchpad. Because compactness for different classes of stimuli may vary across type or level of ability, however, the enhanced span performance for mathematically talented youth could represent a general benefit in working-memory capacity, or it could represent a content-specific factor (i.e., could be a function of compactness).

To distinguish between these possibilities, letters and words were included as items in a span task in addition to digits and locations. If letters and words, as linguistic stimuli, have more compact representations in the verbally talented, and if there is no general capacity benefit for the mathematically talented, then the verbally talented should show better performance than the mathematically talented with letters and words. If, on the other hand, the span difference reported by Dark and Benbow is a function of general representational capacity, the mathematically talented should show a span advantage for all types of stimuli. Because increased working-memory capacity has been identified with higher verbal ability (e.g., Wechsler, 1974), we hypothesized that the former pattern would occur.

Dark and Benbow measured the effectiveness of the operations of working memory's central executive with a continuous paired-associate task in which five stimulus letters were each paired with a digit or a location. The to-be-associated digit or location changed continually. Thus, subjects had to continually update their representations. The mathematically precocious youth showed superior performance. Similar results were reported by Hunt et al. (1973) with college students. The present study included letter–letter pairs in addition to letter–digit and letter–location pairs. We hypothesized that the mathematically precocious youth would show enhanced performance even with letter–letter pairs, because performance depends primarily on working-memory operations and enhanced operations are a function of mathematical talent. If performance depends more on familiarity of the representation than on the effectiveness of the operations, however, and if letter representations are more compact for verbally precocious youth because they are linguistic, then the hypothesis would not be confirmed, because verbally precocious youth would show enhanced performance with letter–letter pairs.

Method

Subjects. Seventy-seven 13- or 14-year-old youth (44 boys and 33 girls), who had just finished seventh or eighth grade, served as subjects. They were participating in a summer program designed for highly gifted youth in which college-level study was required. To qualify for the program, the youth must have scored as a seventh grader at the level of college-bound high school senior boys on either the mathematics portion of the SAT (SAT–M ≥ 500) or the verbal portion (SAT–V ≥ 430). Students were expected to participate in research projects as part of their educational experience and in return for a financial subsidy to the program, but individual participation was voluntary. Students with the highest SAT–M and SAT–V scores were recruited as subjects from four different sessions over two summers.

We defined three groups of gifted youth: youth who showed extreme mathematical and verbal precocity (MV), youth who showed extreme mathematical precocity but were somewhat less extreme in verbal ability (Mv), and youth who showed extreme verbal precocity but were somewhat less extreme in mathematical ability (mV). The terms *extreme* and *less extreme* are used as descriptors, rather than *high* and *low*, because the differences were defined within a group of highly gifted youth. Sixty-four students were placed into one of the three ability groups on the basis of their SAT scores. The MV group comprised 20 students (15 boys and 5 girls) who had SAT–M scores greater than or equal to 580 and SAT–V scores greater than or equal to 490. The Mv group comprised 22 students (17 boys and 5 girls) who had SAT–M scores greater than or equal to 580 and SAT–V scores less than or equal to 450. The mV group comprised 19 students (8 boys and 11 girls) with SAT–M scores less than or equal to 550 and SAT–V scores greater than or equal to 490. Three students (1 boy and 2 girls) with converted American College Testing Program Assessment (ACT) to SAT composites greater than or equal to 1049 and with ACT–Math scores less than 21 were also included in the mV group, for a total of 22 students.

The SAT–M and SAT–V scores for the total sample and the three subgroups are presented in Table 1. Because of the cutoffs used to define the groups, each of the mathematically talented groups was reliably higher than the mV group on SAT–M, $t(37) = 7.81$, $SE = 27.0$, for MV, and $t(39) = 8.00$, $SE = 24.5$, for Mv; each of the two verbally talented groups was higher on SAT–V than the Mv group, $t(40) = 11.13$, $SE = 12.4$, for MV, and $t(39) = 10.00$, $SE = 11.8$, for mV. Our plan of analysis, described in the next section, required that the mathematically talented groups be comparable on SAT–M; there was no reliable difference between them, $|t| < 1$. The plan of analysis also required that the verbally talented groups be comparable on SAT–V; there was no reliable difference between them, $t(37) = 1.46$, $SE = 13.7$.

Plan of analysis. Both analyses of variance (ANOVAs) and multiple regression analyses were used. The ANOVAs are discussed first.

The research was designed to allow the use of planned comparisons (or a priori contrasts) within an ANOVA (e.g., Hays, 1973; Keppel, 1973; Kirk, 1968). Only the subset of youth in the three ability groups was included in these analyses. For each task, there was an a priori hypothesis that either verbal or mathematical talent would lead to better performance. The hypothesis was tested with two comparisons. The first comparison determined whether youth who were extreme in the talent of interest performed better than youth who were less extreme. Thus, the MV and Mv groups were compared with the mV group when mathematical talent was thought to be important, and the MV and mV groups were compared with the Mv group when verbal talent was thought to be important. Because the hypothesis was directional, favoring the combined groups, the comparison was

Table 1
Average Test Scores for the Different Groups

		SAT–M		SAT–V	
Group	N^a	*M*	*SD*	*M*	*SD*
MV	20	664	73	546	44
Mv	22	649	56	408	33
mV	19	453	90	526	39
Total	74	582	113	480	74

Note. SAT–M = Scholastic Aptitude Test, mathematical ability score; SAT–V = Scholastic Aptitude Test, verbal ability score; MV = extreme mathematical and verbal ability; Mv = extreme mathematical and less-extreme verbal ability; mV = less-extreme mathematical and extreme verbal ability.

[a] Scores were not available for three mV students selected on the basis of American College Testing Program Assessment scores.

evaluated with a one-tailed t test with alpha set to .05. The comparison weights were 1, 1, and −2.

In cases in which the first comparison showed no reliable difference, the hypothesis of the importance of the specific ability was rejected and no further analyses were done. In cases in which the first comparison supported the hypothesis, however, a second comparison was performed to assess whether the difference could be attributed to general, rather than specific, ability. The second comparison tested whether the more generally able youth, the MV group, performed at a higher level than the other group extreme in the specific ability. Thus, performance of the MV youth was compared with that of Mv youth for hypotheses involving mathematical talent, and it was compared with that of the mV youth for hypotheses involving verbal talent. The comparison was evaluated using a one-tailed t test with alpha set to .05. The hypothesis that a specific ability is important was supported when the second comparison showed no reliable difference.

To aid interpretation of differences with the comparisons, effect sizes, $d = (M1 - M2)/SD$, are reported (Cohen, 1977). When more than two means were included in a comparison, the average group difference was used in the numerator. The standard deviation in each case was obtained from the entire sample of gifted youth. Cohen (1977) arbitrarily classified effect sizes as small if $.2 \leq d < .5$, medium if $.5 \leq d < .8$, and large if $d \geq .8$.

In our second approach to analyzing the data, both SAT–M and SAT–V were predicted, separately, by multiple regression from performance on the various tasks. All subjects (except for the three with ACT scores), including those not assigned to ability groups, were included in the regression analyses.

Experimenter error resulted in the loss of data in some analyses. In addition, the data of eight youth in the span analysis and one youth in the continuous paired-associate analysis were excluded because the youth failed to follow instructions. The actual number of subjects in each group is reported separately for each task.

Equipment. Stimulus presentation and some response recording were controlled by an Apple II computer equipped with a Timemaster II clockcard and operating under the APT software package (Foltz & Poltrock, 1985). A symmetric 10-cell matrix drawn in thick black lines was taped across the lower half of the computer screen. The matrix was 5.9 cm high and 8.3 cm wide in the middle row. There were three cells in the first row, four in the middle row, and three cells in the last row. Each cell of the matrix defined a spatial location stimulus for the span and continuous paired-associate tasks. All stimuli other than the location stimuli appeared centered in the top half of the screen.

Span tasks. Twenty lists were presented with each of four types of stimuli: digits, letters, words, and locations. For each type of stimulus, five lists were presented at each of four lengths, beginning with the shortest length. A list was scored as correctly recalled only if all items were recalled in the correct order. Each trial began with a ready signal, followed by the items. The ready signal and alphanumeric items were presented in the center of the display area for 800 ms each, with 200 ms between items. After the last item in the list, subjects recorded their answers on a response sheet. Digit, letter, and word lists ranged in length from five to eight items.

Location lists ranged in length from four to seven items. Location items consisted of an asterisk presented for 800 ms in the middle of a cell in the matrix. A location list, therefore, consisted of an asterisk occurring in one cell, and then another, and so on, until the list was complete. There was a 200-ms interval between items. The response sheet for asterisk lists contained blank matrixes. Subjects indicated the order of asterisks by writing the digits *1* through *7*, as needed, in the appropriate cells.

Within an item type, all subjects saw the same lists. Stimulus lists with digits, letters, and locations were constructed by randomly sampling with replacement from the set of 10 digits, from a set of 10 consonant letters (*N, P, Q, R, S, T, V, W, X, Z*), and from the set of 10 matrix locations. No item was immediately repeated in the list. The word lists were constructed by selecting nouns three to six letters long found in the norms of Paivio, Yuille, and Madigan (1968). Each word was used only once.

Continuous paired-associate tasks. There were three types of to-be-associated stimuli in these tasks: digits, letters, and locations as described for the span tasks. The 24 test trials with each stimulus type began with presentation of the initial pairings of the letters *F, G, H, J,* and *K* with a stimulus (e.g., $F = 9$). Each pair was presented for 2 s with a 750-ms interval between pairs. After initial presentation, the letter of one of the pairs was presented along with a question mark (e.g., $F = ?$). The display remained on until the subject responded. The letter was then presented for 2 s with its new stimulus term. Within each set of 24 trials, there were 10 trials each at Lags 1, 2, and 3 (in which lag refers to the number of tests intervening between the original presentation of an item and its test). There were 14 trials at Lag 4 or greater.

Procedure. Subjects were tested in groups of one to six. All subjects began with the span task and then moved on to the continuous paired-associate task. The experimenter gave a short verbal description of each type of task before subjects individually read more detailed instructions and worked through examples. There were four practice trials with each type of stimulus (digits, letters, words, locations) in the span task. A short list of three pairs and six test trials served as practice for each stimulus type in the continuous paired-associate task. Ordering of stimulus types across groups and over subjects was counterbalanced to ensure that each stimulus type occurred approximately equally often at each ordinal position.

Results and Discussion

Alpha was set to .05 for all analyses reported in both experiments.

Span tasks. Figure 1 shows the proportion of correctly recalled lists for each group and each type of stimulus as a function of list length. A preliminary ANOVA with group as a between-subjects factor and type of stimulus and list length (four levels ranging from shortest to longest) as within-subject factors showed a main effect of list length, $F(3, 159) = 323.68$, $MS_e = 0.0443$; a main effect of type of stimulus, $F(3, 159) = 59.09$, $MS_e = 0.0925$; and an interaction between the two, $F(9, 477) = 8.71$, $MS_e = 0.0371$. There was also a reliable Group × List Length × Type of Stimulus Interaction, $F(18, 477) = 2.35$. No other effects were reliable.

As expected, performance decreased as list length increased. An analysis of the linear trend across list length accounted for 99 percent of the variance, indicating a fairly stable decline. Post-hoc comparisons among the stimulus means using Tukey's honestly significant difference (HSD) procedure showed that performance was best with the digits, worst with the words, and intermediate with the letters and locations, which did not differ. Better performance with digits than letters and with letters than words is typical with span tests (e.g., Brener, 1940; Cavanaugh, 1972; Crannell & Parrish, 1957; Puckett & Kausler, 1984), and better performance with digits than spatial locations replicates the results of Dark and Benbow (1990). The Stimulus × List Length interaction appears to be the result of a steeper drop in performance with the word stimuli. All stimuli were presented at the same 1-s rate. Words are

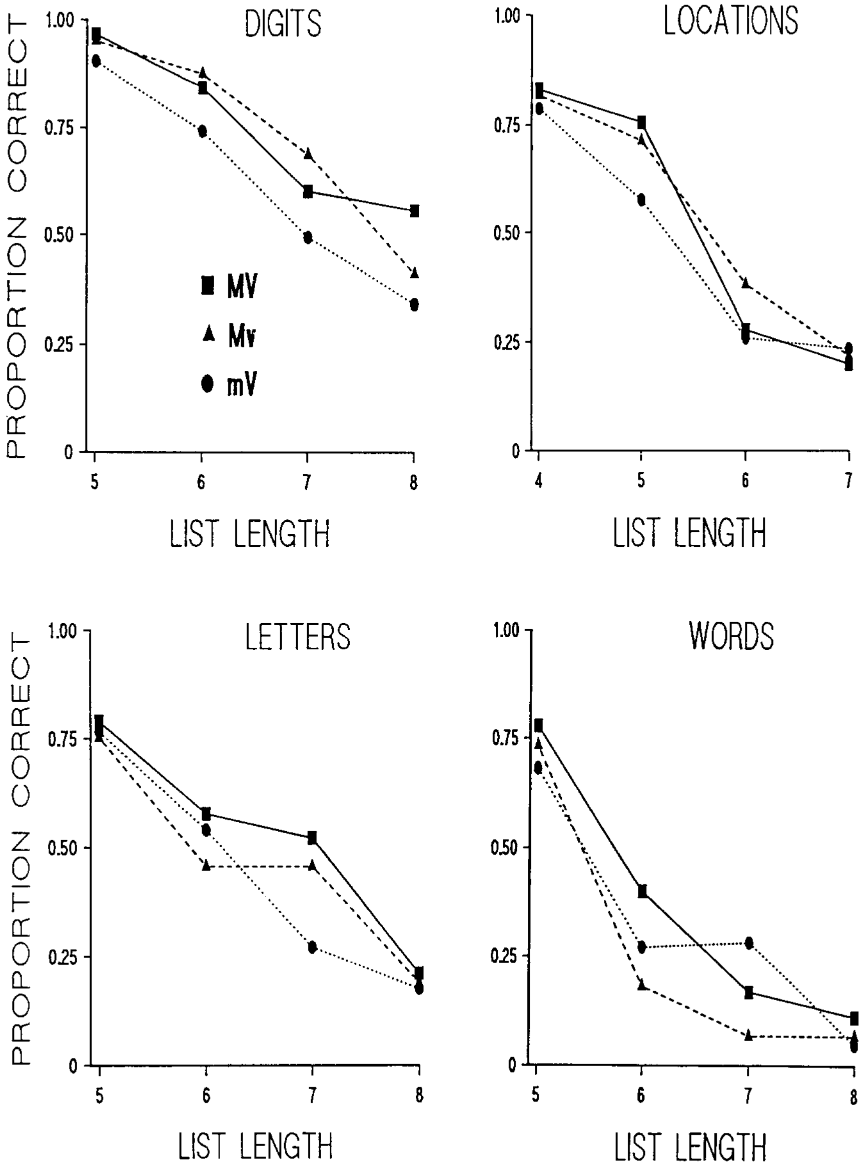

Figure 1. Proportion correct in the span task as a function of list length for each ability group. (Each panel presents data for a different type of stimulus. MV = extreme mathematical and verbal ability; Mv = extreme mathematical and less-extreme verbal ability; mV = less-extreme mathematical and extreme verbal ability.)

perceptually more complex than at least the digit and letter stimuli, and this may have affected performance.

The a priori hypotheses stated that different abilities would be important with different types of stimuli. Although the Group × Type of Stimulus interaction suggested by the hypotheses was not reliable, the Group × Type of Stimulus × List Length interaction was reliable. Inspection of the data suggested the operation of ceiling effects at the shortest list length with all stimulus types and of floor effects at the longest list lengths with all but the digit stimuli. Dark and Benbow (1990) also reported floor and ceiling effects at their longest and shortest list lengths. Although we used a more restricted range of lengths, a similar pattern was obtained. As a result, ability appeared to moderate performance only at the intermediate levels of task difficulty.

To examine the a priori hypotheses without complication of floor and ceiling limitations, a single value was computed for each subject for each type of stimulus. The value for location, letter, and word stimuli was the average of the two intermediate list lengths. The value for the digit stimuli was the average of the three longer lengths. The mean values and standard deviations are shown in Table 2.

Mathematical ability was hypothesized to be important with digit and spatial location stimuli. The hypothesis was confirmed: The MV and Mv groups combined performed better than the mV group with the digit stimuli, $t(53) = 2.00$,

Table 2
Average Proportion Correct as a Function of Group With Different Types of Stimuli in the Span Task

		Type of stimulus							
		Digits		Letters		Words		Locations	
Group	*N*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
MV	18	.667	.208	.550	.220	.283	.207	.517	.223
Mv	21	.657	.192	.457	.289	.124	.134	.548	.229
mV	17	.525	.301	.406	.286	.276	.303	.418	.204
Total	69	.591	.250	.449	.275	.212	.227	.494	.231

Note. MV = extreme mathematical and verbal ability; Mv = extreme mathematical and less-extreme verbal ability; mV = less-extreme mathematical and extreme verbal ability. The proportions for digits are averaged over list lengths of 6, 7, and 8 items; the proportions for other stimulus types are averaged over the two intermediate list lengths.

SE = 0.1367, *d* = .55, and the spatial location stimuli, *t*(53) = 1.79, *SE* = 0.1279, *d* = .50. The MV group did not perform reliably better than the Mv group for either type of stimulus, *d* = .04 for digits and −.07 for locations, supporting the hypothesis that mathematical rather than general talent was related to performance.

Verbal ability was hypothesized to be important with letter and word stimuli. The hypothesis was confirmed for word stimuli: The MV and mV groups combined performed better than the Mv group, *t*(53) = 2.57, *SE* = 0.1212, *d* = .69, and the MV group was no better than the mV group, *d* = .02. The hypothesis was not confirmed for the letter stimuli: There was no reliable difference in the first comparison, *d* = .08. Inspection of the means suggests that general talent may be more related to performance with letter stimuli.

According to the model, digits, letters, and words are maintained in the articulatory loop, whereas location stimuli are maintained in the visuo-spatial sketchpad. Performance on the span tasks can reflect either general capacity or the effectiveness of maintaining encoded information. Because between-groups differences were moderated by stimulus type, there is support for the latter.

The obtained pattern supports an interpretation in terms of differences in compactness of the representations. The compactness explanation also fits the views of Case, Kurland, and Goldberg (1982) and Dempster (1981, 1985), who suggested that span is not so much a measure of general capacity as it is a function of item identifiability: Larger spans occur for items that are more quickly identified. Their emphasis was on perceptual speed. Differences in the compactness of the long-term-memory representations may underlie the differences in perceptual speed.

The differential compactness hypothesis also fits the memory scanning results of Puckett and Kausler (1984), in which scan rate among digit stimuli was predictive of quantitative ability, and scan rate among words (and letters) was predictive of verbal ability in college students. Our verbally precocious youth have more compact word representations, and our mathematically precocious youth have more compact digit representations and more compact representations of location information. Turner and Engle (1989), however, argued that higher ability was, in fact, associated with an increase in general capacity. The current data suggest that *among* high-ability groups, the differences are more content specific; that is, variations in the compactnesss of at least some representations is directly related to type of ability.

Puckett and Kausler (1984) found a reliable correlation between verbal ability and letter span in the general college population, but, contrary to our predictions, there were no differences as a function of verbal ability in the present experiment. Although highly familiar, letters are not usually treated as individual stimuli; that is, they occur in sequences comprising words. Thus, the compactness of letters as individual units may be more equal across groups than the compactness of the other classes of stimuli. Support for this possibility is provided by the data of Palmer, MacLeod, Hunt, and Davidson (1985), in which reading ability correlated with performance in simple tasks using word stimuli but not letter stimuli. Finally, acoustic similarity has been shown to affect span performance (Drewnowski, 1980; Schweickert, Guentert, & Hersberger, 1990). The letter lists showed more within-list acoustic overlap than the other lists, and this may have mitigated any group differences.

The current research was intended to elucidate the characteristics of verbal and mathematical precocity, and we have attributed obtained differences to ability. The subjects were selected on the basis of their SAT scores, and because there are sex differences in SAT-M scores in the gifted population (Benbow & Stanley, 1980, 1981, 1983), the resulting groups did not have equal numbers of male and female subjects. In other words, ability (as defined by SAT score) and sex were confounded in the sample, just as they are in the population. One might, therefore, ask whether the differences that we have attributed to ability are really differences associated with sex. Although there is no easy way to untangle the confound between these two subject variables, we explored the question by performing for each type of stimulus a 2 × 3 unequal *N* ANOVA based on Type III (or partial) sums of squares (SAS Institute, 1985) in which sex and ability group were between-subjects variables. The a priori comparisons concerning ability were then tested within this framework.

There was no reliable main effect of sex and no Sex × Group interaction in the analysis of the digit stimuli. The comparison over groups, however, showed that the four extreme math groups performed at a higher level than the two less extreme groups, *t*(50) = 1.83, *SE* = 0.2985, *d* = .54. There was no reliable difference between the two sets of extreme math groups, $d = -.02$. Boys performed at a higher level than girls with the spatial location stimuli (.558 vs. .372), $F(1, 50) = 7.50$, $MS_e = 0.0443$, just as they did in the study by Dark and Benbow (1990). There was no indication of a Sex × Group interaction and—in contrast to the results of the analysis in which sex was ignored—no support for the a priori hypothesis that mathematical talent was related to performance, $t(50) = 0.85$, $SE = 0.2602$, $d = .24$. There were no reliable differences with the letter stimuli, but the Sex × Group interaction approached significance, $F(2, 50) = 2.77$, $MS_e = 0.0673$, $.05 < p < .10$. The interaction was largely the result of very high performance (.70) by the five Mv girls. The a priori comparison did not show a reliable difference, $d = -.29$. Finally, there was no main effect of sex and no reliable Sex × Group interaction in the analysis of the word stimuli. The comparison over groups, however, showed that the four extreme verbal groups performed at a higher level than the two less extreme groups, $t(50) = 2.61$, $SE = 0.2810$, $d = .81$. There was no reliable difference between the MV and Mv groups, $d = .11$.

Thus, even when sex is "controlled for" in the analysis, there is still some support for the differential compactness hypothesis. Mathematically talented youth, both girls and boys, showed enhanced performance with digit stimuli in a span task, and verbally talented youth, both girls and boys, showed enhanced performance with word stimuli. The only major change in the results was that extreme mathematical ability was no longer associated with enhanced performance with the location stimuli. Boys, regardless of ability, showed better performance than girls with location stimuli.

Continuous paired-associate tasks. Proportion correct for each lag is shown in Figure 2 for each group and each type of stimulus. A preliminary ANOVA with group as a between-subjects factor and lag and type of stimulus as within-subject factors showed a main effect of group, $F(2, 60) = 4.73$, $MS_e = 0.2692$; a main effect of lag, $F(3, 180) = 24.39$, $MS_e = 0.0193$; a main effect of type of stimulus, $F(2, 120) = 9.10$, $MS_e = 0.1065$; and a Lag × Stimulus interaction, $F(6, 360) = 3.92$, $MS_e = 0.0201$. No interaction involving group was reliable.

A comparison among the stimulus means using Tukey's HSD test showed that performance was lower with the letter–letter pairs than with the letter–digit and letter–location pairs, which did not differ. Underwood (1951) reported that paired-associate learning is hindered when stimulus and response terms in word–word pairs are confusable with each other. A similar phenomenon may have occurred in the letter–letter pairs. A comparison among the lag means using Tukey's HSD test showed that performance was highest at Lag 1, intermediate at Lag 2, and lowest at Lags 3 and 4, which did not differ. The pattern of decreased performance and then leveling off at some asymptotic value as the number of events between study and test increase is quite typical in investigations of working memory (e.g., Atkinson & Shiffrin, 1968). Simple main effects analyses of the Lag × Stimulus interaction with alpha evenly split over the effects showed (a) a lag effect for digit and location stimuli but not for the letter stimuli ($\alpha = .016$) and (b) stimulus effects at each lag ($\alpha = .0125$).

The continuous paired-associate task was assumed to reflect the ability to manipulate information in working memory, and the a priori hypothesis was that mathematical talent

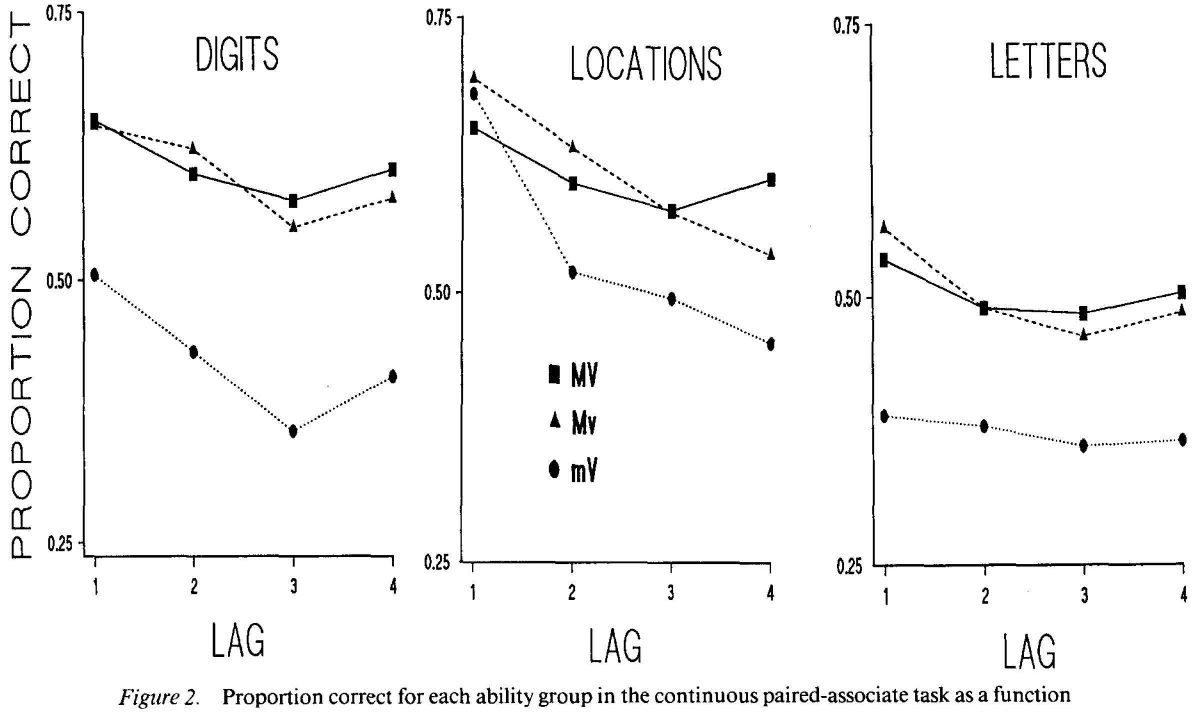

Figure 2. Proportion correct for each ability group in the continuous paired-associate task as a function of lag between presentation and test of a pair. (Each panel presents data for a different type of stimulus. MV = extreme mathematical and verbal ability; Mv = extreme mathematical and less-extreme verbal ability; mV = less-extreme mathematical and extreme verbal ability.)

Table 3
Average Proportion Correct (Collapsed Over Lag) as a Function of Group With Different Types of Stimuli in the Continous Paired Associate Task

		Type of stimulus					
		Digits		Letters		Locations	
Group	*N*	*M*	*SD*	*M*	*SD*	*M*	*SD*
MV	20	.607	.276	.503	.263	.597	.172
Mv	22	.599	.235	.501	.179	.609	.139
mV	21	.426	.167	.375	.194	.537	.135
Total	76	.525	.230	.456	.216	.583	.145

Note. MV = extreme mathematical and verbal ability; Mv = extreme mathematical and less-extreme verbal ability; mV = less-extreme mathematical and extreme verbal ability.

would be important to performance regardless of stimulus type. Although there was no indication that group and type of stimulus interacted, the hypothesis was tested separately for each stimulus type averaged across lag. The averages are shown in Table 3. The hypothesis was supported with digit stimuli and letter stimuli. In each case, the combined MV and Mv groups performed better than the mV group, $t(60) = 2.89$, $SE = 0.1227$, $d = .77$, for digits, and $t(60) = 2.22$, $SE = 0.1143$, $d = .59$, for letters. Although the means showed the predicted pattern with the location stimuli, the comparison did not show a reliable difference, $t(60) = 1.66$, $SE = 0.0797$, $.05 < p < .10$, $d = .46$. The MV group was not reliably better than the Mv group for any type of stimulus, $d = .03$ for digits, $d = .01$ for letters, and $d = -.08$ for locations, supporting the hypothesis that the obtained differences were related to mathematical talent rather than general talent.

The data replicate the results reported by Dark and Benbow (1990) for digit stimuli and extend it to include letters. Although the difference favoring mathematical ability with spatial location stimuli was not reliable, the pattern was similar to that reported by Dark and Benbow (1990), and there was no indication of a Group × Stimulus interaction in the preliminary analysis. The data also confirm the results of an experiment reported by Hunt et al. (1973). College students of varying verbal and quantitative ability performed a continuous paired-associate task in which pairs consisted of a nonsense syllable and a two-digit number. In fitting performance to parameters of the Atkinson and Shiffrin (1968) memory model, Hunt et al. found that quantitative ability was more predictive of continuous paired-associate performance than was verbal ability. High quantitative ability was associated with slower loss of information from working memory.

Expressed within our theoretical framework, the present results and those of Dark and Benbow (1990) and Hunt et al. (1973) suggest that a correlate of mathematical talent is the ability to continually update or change information in working memory. Stimulus familiarity does not strongly moderate performance, suggesting that performance differences reflect operations rather than representations. Word stimuli, which exhibited enhanced performance for the verbally precocious in the span task, were not used in the associative task, however.

The continuous paired-associate data were also examined with ANOVAs in which sex and group were between-subjects variables. With digit stimuli, although boys performed at a higher level than girls (.608 vs. .433), $F(1, 57) = 4.98$, $MS_e = 0.0494$, there was no indication of a Sex × Group interaction. The a priori comparison computed over the six groups supported the hypothesis that mathematical talent was related to performance, $t(57) = 1.89$, $SE = 0.2566$, $d = .53$. The MV group was not reliably better than the Mv group, $d = .00$. There was no reliable sex effect or interaction with the spatial location stimuli, nor did the comparison show a reliable ability effect, $d = .37$. There were no reliable effects with the letter stimuli, but the a priori comparison computed over the six groups approached significance, $t(57) = 1.57$, $SE = 0.2500$, $.05 < p < .10$, $d = .45$. Although the evidence is weaker when sex is controlled for, there is still evidence that working-memory operations, particularly those involving digits, are enhanced in youth who are mathematically precocious.

Predicting SAT. Discussion of the data thus far has been of differences between groups with different ability profiles. An alternative way of looking at the relationship between ability and information processing is to predict SAT performance from performance on the information-processing tasks. The correlations between SAT–M and SAT–V and the various measures are shown in the top portion of Table 4, as are the beta weights and *t* values for each of the statistically significant multiple regressions. Correlations involving SAT–V were adjusted for restriction of range.[2] Both adjusted and unadjusted values are shown.

All of the continuous paired-associate proportions and all of the span proportions, except the one for words, showed significant positive correlations with SAT–M but not SAT–V. SAT–V was related only to word span performance. Using the proportions correct at the intermediate list lengths for each type of stimulus in the span task, we conducted a multiple regression analysis to predict the SAT–M and SAT–V scores. The location proportion was the only reliable contributor to the significant regression for SAT–M ($R = .52$). The regression for SAT–V was significant ($R = .35$) and was due primarily to the word measure. Thus, approximately 27 percent of the variance in SAT–M scores and 12 percent of the variance in SAT–V scores can be accounted for by the ability to represent specific types of information in working memory. The relationship between working-memory capacity and type of precocity is moderated by type of stimulus.

The regression for SAT–V using the continuous paired-associate proportions correct was not significant ($R = .14$). The regression for SAT–M ($R = .44$) was significant, with digits as the only reliable predictor. Almost 19 percent of the variance in SAT–M scores can be accounted for by the ability to maintain and update associations in working memory. Although type of stimulus appeared to be less important with continuous paired-associates than with span, it should be emphasized that word stimuli were not included in the former task.

A multiple regression with forced entry of all the span and the continuous paired-associate measures was able to account

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[2] Compared with the typical population of senior high school students taking the SAT, there was considerable restriction of range of SAT–V scores for the gifted children. We therefore adjusted the correlations as described by McNemar (1969, p. 162).

Table 4
Correlations Between SAT-M and SAT-V and the Various Information Processing Measures, and Beta Weights and t Values for Regression Equations

Task and type of stimulus	SAT-M			SAT-V			
	r	β	t	r	Adjusted r^a	β	t
Span ($n = 67$)							
Digit	.36***	.23	−1.55	−.00	−.00	−.04	−0.27
Location	.43***	.33	2.76**	−.18	−.26	−.17	−1.31
Letter	.25*	.13	0.92	.06	.09	−.01	−0.04
Word	.05	−.18	−1.53	.29**	.41	.31	2.40**
Multiple R	.52***			.35*	.49		
Continuous paired-associate ($n = 73$)							
Digit	.41***	.31	2.37*	−.10	−.15		
Location	.30**	.14	1.18	−.11	−.16		
Letter	.27**	.07	0.58	−.11	−.16		
Multiple R	.44**			.14	.21		
Lexical decision ($n = 74$)							
Latency	.10			−.27**	−.39	−.23	−1.82*
Priming	.14			−.20*	−.29	−.09	0.72
Multiple R	.15			.28*	.40		

Note. SAT-M = Scholastic Aptitude Test, mathematical ability score; SAT-V = Scholastic Aptitude Test, verbal ability score.
[a] Correlations adjusted for truncation of range.
* $p < .05$. ** $p < .01$. *** $p < .001$.

for 34 percent of the variance in SAT-M scores ($R = .58$). Thus, the ability to manipulate information in working memory tapped in the continuous paired-associate task is at least somewhat different from that tapped in the span task.

Experiment 2

Experiment 1 examined the relationship between working-memory accuracy and intellectual ability. Performance was more strongly associated with mathematical than verbal talent. The focus in Experiment 2 is on speed of processing. Several studies have shown that verbal ability is related to the speed with which semantic information is retrieved (activated) from the long-term store into working memory (Ford & Keating, 1981; Hunt et al., 1973, 1975). Verbal precocity may be associated with this component of the information-processing system. That hypothesis was investigated with a lexical-decision task.

In the lexical-decision task, subjects were presented letter-string targets, half of which were common words and half of which were pronounceable nonwords (e.g., FLOME). Subjects categorized the targets as word on nonword with a keypress. The speed of a "word" response can be interpreted as a measure of the time it takes the sensory information to activate a long-term representation into working memory (cf. Meyer, Schvaneveldt, & Ruddy, 1975). We predicted that increased verbal ability would be related to increased lexical-decision speed.

Lexical-decision speed for word targets was measured in both a related and an unrelated context. The context was established by a briefly presented prime word that preceded each target. The prime was semantically related for half the word targets (e.g., BABY INFANT) and unrelated for the other half (e.g., BOOK INFANT). Decision speed is generally faster for word targets in a related context; this benefit relative to the unrelated context is called semantic *priming*, because it reflects the influence of the semantic content of the prime. Priming effects are often smaller for faster subjects (e.g., Carr, 1981; Fischler & Goodman, 1978). We therefore predicted that verbally talented youth would show less priming.

A third measure obtained as part of the lexical-decision task was recognition. After the lexical-decision trials, subjects completed an unexpected recognition test of the primes that had preceded the word targets. Recognition performance depends on the level (rather than speed) of processing in working memory (Craik & Tulving, 1975; Eich, 1984; Fisk & Schneider, 1984; Smith, Theodor, & Franklin, 1983) and, therefore, complemented our other measures. We had no a priori prediction concerning recognition performance.

Method

The subjects described in Experiment 1 also participated in Experiment 2. The plan of statistical analyses described in Experiment 1 was used.

The equipment and software described in Experiment 1 were used for stimulus presentation and response collection. A complete description of the word sets comprising related-prime/unrelated-prime/target triads can be found in Experiment 1 of Dark (1988). Each of 88 trials began with the presentation of a ready signal for 500 ms, which was followed after 750 ms by a prime. The prime, which was a common English word, was presented for 133 ms and then masked by a row of *X*s. One second after prime onset, the target occurred. The target was a word on half the trials and a pronounceable nonword on the other half. The target remained on the screen until the subject made a lexical decision by pressing one of two keys labeled *Y* (yes, it is a word) and *N* (no, it is not a word). The intertrial interval was 1250 ms. Decision latencies were measured. Those latencies that were less than 150 ms or greater than two standard deviations above each subject's mean (<5%) were discarded.

Table 5
Lexical-Decision Accuracy, Decision Latency (in Milliseconds) for Each Type of Target, and Semantic Priming as a Function of Group

			Latency									
			Nonword		Unrelated		Related		Average		Priming[a]	
Group	*N*	Accuracy	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
MV	20	.96	647	126	586	109	545	94	593	104	41	66
Mv	22	.93	748	188	705	237	624	143	693	181	81	151
mV	22	.96	703	165	621	129	595	141	640	135	26	61
Total	77	.95	688	157	625	165	577	127	630	142	48	95

Note. MV = extreme mathematical and verbal ability; Mv = extreme mathematical and less-extreme verbal ability; mV = less-extreme mathematical and extreme verbal ability.
[a] Priming was computed as the unrelated word latency minus the related word latency.

Results and Discussion

Latency. Overall decision accuracy and decision latency (for correct responses) for each type of target are presented for each group in Table 5. An ANOVA performed on the latency data with ability group as a between-subjects factor and type of target as a within-subject factor showed a reliable effect of type of target, $F(2, 122) = 42.88$, $MS_e = 4{,}632$. The group main effect only approached significance, $F(2, 61) = 2.51$, $MS_e = 62{,}628$, $.05 < p < .10$, and there was no reliable interaction. Application of Tukey's HSD test to the target means collapsed over group showed a typical pattern: Latency to the related-word targets was faster than to the unrelated-word targets, which was faster than to the nonword targets.

Because there was no indication of an interaction, the planned comparisons between the groups was performed on latency collapsed over type of target. As predicted, the extreme verbally talented groups (MV and mV) were reliably faster than the Mv group, $t(61) = 2.01$, $SE = 76.1$, $d = .54$. The MV group was not reliably faster than the mV group, $d = .33$. The data support the assertion that speed of activating a word's representation from long-term memory into working memory (i.e., speed of working-memory encoding) is a correlate of verbal ability.

Priming. Even though the Stimulus × Group interaction in the latency ANOVA was not reliable, a portion of that interaction was examined with the priming measure. Priming was computed by subtracting the latency for the word targets following related primes from the latency for word targets following unrelated primes and is shown in Table 5. Directional t tests (with alpha set at .05) showed that priming was reliably greater than zero for each group: $t(19) = 2.70$, $SE = 15.16$, for MV; $t(21) = 2.45$, $SE = 33.04$, for Mv; $t(21) = 1.97$, $SE = 13.22$, for mV. As predicted, the two verbally talented groups showed reliably less priming than the Mv youth, $t(61) = 1.76$, $SE = 54.00$, $d = .50$. The MV group did not show less priming than the mV group, $d = -.16$, supporting the hypothesis that verbal ability, not general ability, was related to a lower level of priming.

Faster latencies to targets in a lexical-decision task that are followed by related words has been attributed, at least in part, to postlexical operations involving the representations of both the prime and the target (e.g., de Groot, 1984; Neely, 1990; Neely & Keefe, 1989; Norris, 1986; Ratcliff & McKoon, 1988). Within the working-memory framework, then, priming in a lexical-decision task can result from working-memory operations occurring after the target has been encoded into working memory. The Mv group may have shown more benefit with related targets because performance in a related context reflects working-memory operations and not just the speed with which sensory information can activate a long-term-memory representation.

Carr (1981) reviewed the reading literature and concluded that poor readers generally show more priming than good readers, because the poor readers rely on attentional (working-memory) processes whereas the good readers rely on more automatic processes. Our explanation for the difference in priming between extremely verbally talented youth and less extremely verbally talented youth relies on a similar distinction. When the mean decision latency for related words for the Mv students was compared with that of unrelated words for the MV and mV groups, they were not reliably different ($F < 1$). Whatever the additional working-memory operation that was enabled by a related context, it allowed mathematically gifted youth with less extreme verbal ability to function at the same level as extremely verbally talented youth in an unrelated context.

Recognition. There were no differences among the groups in the proportion correct on the recognition test. The averages were .78 ($SD = .11$) for the MV group, .80 ($SD = .10$) for the Mv group, and .80 ($SD = .08$) for the mV group. Although students with high verbal ability appear to have quicker access to information in long-term memory, the increased speed does not appear to enhance the total processing, at least as measured in a delayed recognition test.

The evidence for ability differences in speed of encoding dissipated when sex and group were both included as variables in an ANOVA. Girls were faster than boys in making the lexical decision (595 ms vs. 670 ms), $F(1, 58) = 4.24$, $MS_e = 20{,}343$, and there was no indication of a Sex × Group interaction. The a priori comparison computed over the six groups did not show any reliable difference ($d = .34$). There was no reliable sex difference or indication of a Sex × Group interaction with either priming or recognition. The a priori comparison for priming did not show a reliable difference ($d = .28$).

Predicting SAT. SAT–V and SAT–M were predicted by performance on the lexical-decision task. As in Experiment

1, the values predicting SAT–V were adjusted because of restriction of range. The correlations between SAT–M and SAT–V and the various measures are shown in the lower portion of Table 4. The measures correlate with SAT–V and not SAT–M. SAT–M is not predicted by any measure. A multiple regression analysis predicting SAT–M from latency and priming was not significant ($R = .15$). SAT–V, however, was significant ($R = .28$). The analyses confirm that faster encoding of information in working memory is a correlate of verbal precocity, at least for wordlike stimuli. The failure of SAT–M to be predicted suggests that the abilities to maintain and manipulate information explored in Experiment 1 are not abilities used in encoding.

The overall pattern found in Experiment 2 suggests that speed of encoding in general is more strongly associated with verbal precocity than with mathematical precocity. Thus, the data are consistent with the work of Ford and Keating (1981) and Hunt et al. (1973, 1975), which showed that quick access to verbal information in long-term memory was correlated with higher verbal ability in college students. The analyses including sex as a control variable, however, show the need for further research in this area: Sex may be more strongly related to encoding speed than is verbal ability.

General Discussion

The two experiments described herein represent the cognitive-correlates approach to individual differences, in which performance on complex tasks, such as the SAT, is examined in terms of performance on basic information-processing tasks. The approach looks for differences in three general categories comprising the "mechanistic aspects" of thought (Hunt, 1978, 1983): differences in encoding information, differences in manipulating information in working memory, and differences in storing information in long-term memory. For the most part, the approach has been used to determine the information-processing skills that are correlated with high versus low ability on some dimension (e.g., Cohn et al., 1985; Hunt, 1978; Hunt et al., 1975).

The current research builds upon the work of Dark and Benbow (1990) in using the approach to distinguish between differentially talented, high-ability youth. By using different kinds of stimuli in a variety of tasks, we have found evidence indicating that the ability to manipulate information in working memory is a correlate of mathematical talent. In contrast, enhanced retrieval (encoding) of a representation from long-term memory into working memory appears to be a component of verbal talent. Finally, working-memory representational capacity varies differentially between ability groups as a function of the type of stimulus.

This latter point is, we think, very important. Jackson and Butterfield (1986) expressed concern that there was no way of knowing from results of previous studies whether differences in performance on memory tasks between gifted and average-ability individuals were attributable to a general efficiency of the gifted group's memory processes (i.e., differences in working-memory operations) or to the gifted children's greater familiarity with letter and number stimuli (i.e., differences in long-term-memory representations). Our results emphasize the validity of this concern. Differences between groups of highly gifted youth appeared on some tasks to be dependent on the talent of the youth and the type of item. Even when the stimuli were just to be recognized and named, mathematically precocious youth were better able to handle digit stimuli, whereas verbally precocious youth were better able to handle word stimuli. Thus, stimulus characteristics moderated performance on simple working-memory tasks.

We have called the above characteristic *compactness* or *familiarity*, but it could be *meaningfulness*, or a variety of other alternatives. Whatever the characteristic, however, we suggest that it is more related to representational differences in long-term memory than to differences in working-memory operations. In the articulatory loop, mathematically talented youth more efficiently represented digit stimuli, and verbally talented youth more efficiently represented word stimuli. Mathematically talented youth were more efficient in representing information in the visuo-spatial sketchpad.

Our research also emphasizes the importance of considering types of giftedness and types of task. Verbal and mathematical giftedness are different, but at least somewhat correlated (Stanley, 1988). Similarly, memory is a complex system, and individuals can vary in different ways. Earlier studies relating intellectual ability to enhanced memory functioning did not always separate verbal and mathematical ability (Borkowski & Peck, 1986; Ford & Keating, 1981; Hunt et al., 1975; Keating & Bobbitt, 1978; McCauley, Kellas, Dugas, & DeVillis, 1976), and the tasks reflected primarily speed of encoding. The results of the current research and those of Dark and Benbow (1990) and Hunt et al. (1973) suggest that enhanced working-memory operations are more strongly associated with mathematical talent, whereas speed of encoding is more strongly associated with verbal talent.

Sex and ability were confounded in our sample. They did not reliably interact, however, and so we collapsed across sex in our primary analyses. Still, it is possible that some of our ability differences are more appropriately labeled sex differences. The results continued to suggest that working-memory operations are enhanced in mathematically talented youth when sex was a factor in the analysis. Encoding speed, on the other hand, might be associated with sex but not verbal ability. Although interesting, the sex difference analyses must be treated cautiously, because the sample of mathematically talented girls was very small.

Our research is exploratory. Clearly, the findings need to be replicated by ourselves and others. The generalizability of the results also must be determined. We have contrasted mathematical and verbal talent only among the extremely talented, and we have not fully addressed the confounding between sex and ability. The emerging picture relating specific information-processing abilities to specific intellectual abilities is, however, fascinating. At the very least, our research emphasizes that performance is complexly determined by the task, the stimulus, and the individual. It also demonstrates the potential of the cognitive-correlates approach as a tool for understanding the nature of individual differences. The approach provides the rapprochement between those interested in individual differences and those interested in cognitive psychology that has been desired for at least the last 30 years (Cronbach, 1957; Green, 1988).

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