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Type of Stimulus Mediates the Relationship Between Working-Memory Performance and Type of Precocity

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The relationship between type of stimulus (numeric and verbal) and type of precocity (mathematical and verbal) was examined in tasks designed to tap three aspects of working memory: encoding, capacity, and manipulation of information. The tasks included semantic categorization, odd-even categorization, recall of five-item lists after semantic categorization, and recall of items in a continuous paired-associates task. Correlations between task performance and the mathematical and verbal portions of the Scholastic Aptitude Test (SAT-M and SAT-V) were computed for gifted youth. There were no sex differences in the performance measures or in the pattern of correlations between performance and SAT scores. The analysis revealed positive relationships between SAT-M scores and numeric categorization latency, recall in the continuous paired-associate task with words and digits, and recall of digit lists. SAT-V scores were related only to word recall in the continuous paired-associate task and recall of word lists. In the working-memory tasks used, mathematical precocity is more strongly related to performance than is verbal precocity. The relationship is especially strong with numeric stimuli, even when the numeric stimuli are simply items to be remembered. The relationship between type of stimulus and type of precocity suggests underlying differences between verbally and mathematically precocious youth in how different types of stimuli are represented in memory.

For those working in the area of individual differences, differences found in intellectual ability are of particular interest. The cognitive correlates approach is a framework within which psychometrically defined differences in intelligence can be examined and their nature clarified. This framework is built on the assumption that persons higher in intellectual ability are also more alert to information in the environment (Hunt, 1978); thus, it assumes that differences in performance on complex tasks, like cognitive ability tests, can be understood by examining their relationships with performance on very simple information-

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processing tasks (e.g., Cooper & Regan, 1982; Hunt, Frost, & Lunneborg, 1973; Hunt, Lunneborg, & Lewis, 1975). The information-processing tasks are designed to tap into what Hunt (1978, 1983) referred to as the "mechanistic aspects of thought," operations like stimulus encoding, maintenance of representations in working memory, and manipulation of representations in working memory.

There is a fairly large cognitive correlates literature examining the relationship between general intellectual ability and working-memory capacity as well as processing speed (or encoding and decision speed). For the most part, the literature shows that more intellectually able individuals are faster in encoding and scanning information and have better memory in general (e.g., Belmont & Butterfield, 1971; Cohen & Sandberg, 1977; Cohn, Carlson, & Jensen, 1985; Hunt, 1976, 1978; Hunt et al., 1973; Hunt et al., 1975; Keating & Bobbitt, 1978; Vernon, 1983; see Dark & Benbow, 1993, for a review). Dark and Benbow (1990, 1991, 1993) expanded on this earlier research by asking whether or not there would be individual differences in memory span and speed of encoding as a function of *type of intellectual giftedness:* mathematical versus verbal. Dark and Benbow reasoned that each of these psychometrically distinguishable forms of giftedness (Benbow & Minor, 1990) should be associated with a different set of superior information-processing skills. Because they couched their research within the working-memory model of Baddeley and colleagues (e.g., Baddeley, 1986; Baddeley & Hitch, 1974; Baddeley & Lieberman, 1980), in which different types of stimuli are handled by different subsystems in working memory, Dark and Benbow also examined performances as a function of *type of stimulus* (digits, letters, words, and spatial locations in a matrix). Differences in forms of giftedness, it was argued, may lie in the ability to process certain types of stimuli and not in the processes themselves.

Using intellectually precocious 13- and 14-year-old youth as research participants, Dark and Benbow found three relationships between ability and performance and type of stimulus. First, mathematical precocity was related to enhanced performance on a working-memory span task with digit and location stimuli (Dark & Benbow, 1990, 1991), but verbal precocity was related to enhanced performance with word stimuli (Dark & Benbow, 1991). These relationships held even when sex of participant was a factor in the analysis. Thus, enhanced working-memory capacity was stimulus specific.

Second, mathematical precocity was associated with increased ability to manipulate information in working memory by forming temporary associations among representations of digit, letter, and location stimuli (Dark & Benbow, 1990, 1991), suggesting that the enhanced ability to manipulate information in working memory was a general characteristic of mathematical precocity. Words were not used as stimuli, however. Thus, the generalizability of the relationship across stimulus types was somewhat limited.

Third, verbal precocity appeared to be related to encoding of verbal stimuli:

Verbal precocity was associated with faster decisions about wordlike stimuli in a lexical-decision task (Dark & Benbow, 1991). The precocity differences were not found when sex was a factor in the analysis, however. Thus, it is unclear as to whether sex or precocity was responsible for the relationship. Also, there was no equivalent task with numeric stimuli to ascertain whether encoding in general, or just encoding of verbal material, was being tapped. Although Dark and Benbow (1993) used both types of stimuli and reported that verbal precocity was related to the speed with which word representations could be encoded and compared and that mathematical precocity was related to the speed with which digit representations could be encoded and compared, sex was not examined in that study. Thus, this issue was left unresolved.

The finding that the relationship between working-memory performance and type of precocity varied as a function of type of stimulus suggested that there were differences in how numeric and verbal stimuli were represented within working memory. We described the difference in terms of *compactness* (Dark & Benbow, 1990, 1991). Compact representations, we suggested, are more quickly encoded into working memory, are more easily maintained in an active state, and are more easily manipulated by control processes. The data suggested that digit representations are more compact in persons with higher mathematical ability (and thus associated with higher span), whereas word representations are more compact in persons with higher verbal ability. The difference goes beyond the verbal–visual distinction, which is part of Baddeley's (1986) model of working memory, because both numeric and verbal stimuli in the tasks used would be handled within the verbal system.

The aim of the current research was to more precisely define and explore the relationship between type of stimulus, type of precocity, and characteristics of working memory. The research examined the performance of gifted individuals on three tasks that were designed to have at least roughly equivalent numeric and verbal versions. The tasks were categorization, dual-task recall, and continuous paired associates.

Before describing in detail the tasks and their relationship to working memory, however, we note an important difference between this and our earlier research. Dark and Benbow (1990, 1991, 1993) contrasted performance between the most extremely mathematically precocious youth (SAT-M scores ≥ 580 by age 13) and the most extremely verbally precocious youth (SAT-V scores ≥ 490 by age 13). Because extreme mathematical precocity, as measured by SAT-M scores, is found primarily among boys (Benbow, 1988; Lubinski & Benbow, 1992), the precocity comparisons were confounded with sex differences in the groups. Rather than using the strategy of contrasts among differentially talented groups, the current research used correlational analyses to examine the relationship between performance on working-memory tasks and SAT scores. As a result, the participants were a more diverse group of precocious youth, more evenly divided between girls and boys.

Working-Memory Tasks

Categorization. Several studies have suggested that the speed with which semantic information is encoded into working memory (or activated from the long-term store into working memory) is associated with verbal precocity (e.g., Ford & Keating, 1981; Hunt et al., 1973; Hunt et al., 1975). As described earlier, Dark and Benbow (1991, 1993) also found a relationship between encoding speed and verbal precocity. In the current research encoding speed was measured in two binary-categorization tasks: an odd/even judgment about two-digit numbers and an animal/fruit–vegetable judgment about words. Performance in either task requires *encoding* of the stimulus, followed by a *decision* regarding the response class into which it fits. The speed of the two distinct processes cannot be separated easily in these tasks, however (cf. Whitney, Kellas, & Ferraro, 1990). Thus, the two processes together are referred to as encoding. If verbal precocity is associated with faster encoding of words, as is suggested by the literature, it should be associated with faster performance in the verbal (animal/fruit–vegetable) categorization task. If mathematical precocity is associated with faster encoding of numeric information, as suggested by Dark and Benbow (1993), it should be associated with faster performance in the numeric (odd/even) categorization task.

Dual-Task Recall. Previous research (Dark & Benbow, 1990, 1991) already has shown that mathematical precocity is related to memory span for digits and verbal precocity is related to memory span for words. Several studies (e.g., Cantor, Engle, & Hamilton, 1991; Daneman & Carpenter, 1980; Turner & Engle, 1989) have shown that complex span tasks, requiring more than just storage of items, are more strongly related to ability than simple span tasks. We decided, therefore, to use list recall under dual-task conditions as a measure of capacity. Participants were presented five-item lists of either digits or words. The list was followed immediately by a verbal categorization stimulus. List recall occurred after the categorization response. If performance on simple span tasks can be extrapolated to the dual-task situations, then higher accuracy on the digit lists should be related to mathematical precocity and higher accuracy on the word lists should be related to verbal precocity.

Continuous Paired Associates. Dark and Benbow (1990, 1991) and Hunt et al. (1973) found that those higher in mathematical ability did better on a continuous paired-associates task. In a paired-associates task, participants must learn item pairs such that when they are given the first item in the pair, they are able to produce the second item. In the continuous version of a paired-associates task, the first item in the pair is assigned a new response after an item is tested. That is, a new pair is defined using the same first item. Because the to-be-associated response (the second item) is changed continuously, successful performance requires accurately forming and maintaining a set of temporary associations. Long-term learning would only interfere with performance.

Dark and Benbow (1990, 1991) always used letters as the first item in a pair in the continuous paired-associates task, but they varied the type of response item, using digits, letters, and locations in a matrix. Hunt et al. (1973) used nonsense syllables as the first item and two-digit numbers as the response. Consequently, the relationship between performance and ability has not been examined with words as responses. If the working-memory process tapped by the continuous paired-associate task is a general property of mathematical precocity, as suggested by Dark and Benbow (1990, 1991), then mathematical precocity should be related to performance with word responses as well as with digit responses. If, on the other hand, performance is a function of the compactness of the representation, then only verbal precocity should be related to performance with words.

METHOD

Participants

There were 104 11- to 14-year-old youth (61 boys and 43 girls) who served as research participants. The youth consisted of students enrolled in a 3-week summer program at Iowa State University designed for gifted youth. To qualify for the program, the youth must have scored by age 13 at 500 or more on SAT-M, at 430 or above on SAT-V, or at 930 or above for the two combined.[1] The minimum scores reflect the averages for college-bound high school senior males, who are 4 to 5 years older than the youth in the program.

Data were collected over 2 years. During the first year, all program participants with SAT scores were invited to participate in the research in exchange for attendance at a pizza party during the last week of the program. Eighty-three students participated. During the second year, 21 students (9 girls and 12 boys) with the highest SAT scores were recruited as participants; they were paid $5.

The mean SAT-M and SAT-V scores for the sample are presented in Table 1 by sex along with the standard deviations. The boys in the sample had reliably higher scores than the girls on SAT-M, $t(102) = 4.12$, $SE = 17.4$. There was no sex difference in the SAT-V scores.

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[1] Youth applying to the summer program can establish their qualifications via either SAT scores or ACT (American College Testing) scores. Because the youth applying to the program take the SAT at different ages, ranging from 10 to 14 years old, we age-adjust the SATs to make them more comparable. For the present research, scores from SATs taken between 144 months and 160 months of age were not adjusted. Scores from SATs taken after 160 months were adjusted downward by 4.6 SAT-V units and by 5.4 SAT-M units per month over 160 months. Scores taken before 120 months were adjusted upward in the same fashion.

TABLE 1
Means and Standard Deviations of SAT Scores for Girls and Boys and the Total Sample

		SAT-M		SAT-V	
	N	*M*	*SD*	*M*	*SD*
Girls	43	507	89	463	93
Boys	61	579	85	450	84
Total	104	549	94	455	88

Note. SAT-M = Scholastic Aptitude Test, mathematical ability score; SAT-V = Scholastic Aptitude Test, verbal ability score.

Stimuli and Equipment

Stimulus presentation and response recording were controlled by an IBM PC computer operating under the APT-PC software package (Foltz & Poltrock, 1985). Stimuli were displayed on an IBM CGA monitor. All stimuli appeared in white on a black background and were centered in the middle of the screen. The character set was twice the height and width of the standard set (i.e., there were 40 characters possible per double-height line).

The keyboard was used for all responses. Across the various tasks there were three classes of responses: digit, word, and binary. Digit responses were indicated either via the numeric keypad located to the right of the standard keyboard or via the digit keys on the top row of the keyboard. The choice was up to the participant and most chose the keypad.

When word responses were required, the word was one of 10 possibilities (*bowl, door, nail, book, rock, ship, tree, star, coin, road*) selected to be single-syllable nouns that were high in frequency, imagery, and concreteness in the norms of Paivio, Yuille, and Madigan (1968).[2] The words were written on labels and attached (in the order specified) to the first five letters in the second and third rows of the keyboard (Q, W, E, R, T, A, S, D, F, G); thus, word responses were also made by a single key press.

There were two binary decisions: animal versus fruit–vegetable in the word categorization task and odd versus even in the number categorization task. The comma and period keys, located on the right in the last row of the keyboard, were used to make these responses. A label on the comma key read "A/O" for animal and odd. A label on the period key read "F–V/E" for fruit–vegetable and even. A 5-in. × 8-in. card braced against the computer had the two alternatives for the left (comma) and right (period) responses spelled out in large letters as a reminder. Participants used the index and middle fingers of their preferred hand to make the binary responses.

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[2] Although ROAD was not in the Paivio et al. (1968) norms, we used it as a four-letter synonym of STREET, which was in the norms.

The word categorization task involved classifying a word as either an animal or a fruit–vegetable. Eighty words were used, 40 from each category. The words were selected from among the top associates (frequency of at least 10) to each of the categories in the norms of Battig and Montague (1969). Words ranged in length from three to eight letters. An additional eight words were selected to be used in practice and as buffers.

The number categorization task involved classifying a two-digit number as either odd or even. All two-digit numbers between 20 and 98 were used with the exception of numbers with repeated digits (e.g., 22, 33). These numbers and two-digit numbers in the range of 10 to 19 were used in practice and as buffers.

Specific Tasks

Simple Categorization. The first tasks for every participant were word categorization and then number categorization. During these tasks, the participants simply classified, as quickly as possible, a stimulus presented in the center of the screen. Each trial began with a ready signal, consisting of two plus signs, presented for 500 ms centered in the middle of the screen. The ready signal was followed, after 200 ms, by the to-be-classified stimulus, also presented in the middle of the screen. The stimulus was displayed until a response was made.

Participants were instructed to rest the index and middle finger of their dominant hand on the appropriate response keys in order to be able to respond quickly. The instructions stated that very few errors were expected and that responses were to be made as quickly and as accurately as possible. Forty stimuli, 20 representing each binary response, were used for each task. A different random ordering of the stimuli within each task was generated for each subject. There were six practice and two initial buffer trials in each task.

Dual-Task Recall. In the dual-task conditions, a verbal (fruit–vegetable/animal) categorization was made while maintaining a five-item list in memory. After each categorization response, the participant recalled the five-item list. Digit memory lists consisted of a set of 5 digits, selected randomly without replacement, from the set of 10 possible digits. Word memory lists consisted of a set of 5 words, selected randomly without replacement, from the 10 words appearing on labels on the keyboard.

Each trial began with the word "READY." The participant then initiated stimulus presentation by pressing one of the two categorization response keys. The five items in the memory list were presented, one at a time, for 800 ms each, followed by a 200-ms blank. One second after the last memory item, the categorization stimulus was presented. It remained on until a response was made. The categorization stimulus was followed by five displays reading "RECALL N," where N began as 1 and incremented to 5 as the participant responded. The participants entered their memory responses by pressing the appropriate keys;

they were instructed to enter a guess when they were unsure about an item because responses would be counted as correct only if they were in the appropriate serial position.

The instructions emphasized accuracy in the memory task. Participants were told that they might need to slow down their categorization responses if quick responses interfered with their ability to recall the items in memory. There were 20 digit lists followed by 20 word lists. Six practice and two initial buffer lists were included for each type of stimulus.

Continuous Paired-Associate Task. The final task was the continuous paired-associate task. In the task, five letter stimuli (F, G, H, J, K) were paired with 1 of 10 responses. After each letter-response pairing was tested, the letter was paired with another response. Thus, the participant had to continuously change the five letter-response pairs being maintained in memory. Two types of responses were used. For the first half of the task, each letter was paired with 1 of the 10 digits. For the second half, each letter was paired with 1 of the 10 words that were indicated by labels on the keyboard.

Each half of the task began with the presentation of the five letters paired with their initial responses. The letter occurred to the left of an equal sign and the response occurred to the right (e.g., F = 9). Each pair was presented for 2,250 ms with a 250-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 by pressing one of the appropriate keys. The letter was then presented for 2,250 ms with its new stimulus term. Either the digits on the numeric keypad or on the top row of the keyboard were used for the digit responses. The keys in the second row of the keyboard labeled with the 10 words were used for the word responses. Participants were informed that accuracy was important in this task and that latency was not recorded.

Thirty trials were presented with each type of stimulus. Within each set of 30 trials, there were 10 trials at lags one or two, 10 trials at lags three or four, and 10 trials at lags five or six (where lag refers to the number of tests intervening between the original presentation of an item and its test). Each lag was used approximately equally often with each letter and each possible response. A practice sequence with three letters and six new pairings of response items occurred for the first version of the task (letter–digit pairs), but there was no additional practice given after the letter–word instructions.

Procedure

Subjects were run in groups of up to 10. The session began with general instructions describing the overall nature of the tasks and describing the different keys to be used for responses. As the experiment progressed, each of the tasks was explained via written instructions on the computer screen and practice was given. All participants went through all tasks in the same order. Participants proceeded through the experiment at their own rate, taking breaks as needed between tasks.

RESULTS AND DISCUSSION

The results are presented with preliminary discussion in three main sections. First, performance on the working-memory tasks is described. Second, the relationship between performance on the working-memory tasks and precocity, assessed via simple correlations, is detailed. Third, the relationship assessed by using multiple regression to predict SAT scores from performance on the working-memory tasks is presented. The results as a whole are discussed in the final section of the article.

For all analyses, an effect was considered statistically reliable if $p < .05$; an effect was defined as not reliable if $p > .10$.

Performance on the Working-Memory Tasks

Categorization. The mean verbal and numeric categorization latency are shown in the top panel of Table 2 as a function of sex. Categorization accuracy was high (95% for the verbal task and 94% for the numeric task) and the latency means were computed only from trials on which the correct response was made. A 2 × 2 analysis of variance (ANOVA) with type of stimulus as a within-subjects variable and sex as a between-subjects variable showed a main effect of type of stimulus, $F(1, 102) = 25.60$, $MSE = 3{,}912$: Numeric categorization was faster than verbal categorization. There were no reliable effects involving sex.

Although both categorization tasks were chosen to reflect encoding and decision speed, the numeric categorization task appeared to be easier. Dark and Benbow (1993) also found faster decisions concerning the match between two digits than the match between two words. They suggested that digits were perceptually

TABLE 2
Means and Standard Errors of Performance on the Working-Memory Tasks as a Function of Sex and Type of Stimulus

Task and Type of Stimulus	Girls		Boys		Total	
	M	*SE*	*M*	*SE*	*M*	*SE*
Categorization Latency (in ms)[a]						
Verbal	675	13	668	12	671	9
Numeric	642	13	613	12	625	9
Dual-Task Recall, Proportion of Lists[b]						
Words	.52	.04	.47	.03	.49	.03
Digits	.88	.02	.86	.02	.87	.01
Proportion Recalled in CPA[a,c]						
Words	.33	.02	.30	.02	.31	.01
Digits	.30	.02	.28	.02	.29	.01

[a] There were 43 girls and 61 boys. [b] There were 37 girls and 49 boys. [c] CPA = continuous paired associates.

simpler than words and, thus, may have been encoded more quickly, leading to faster decisions. The same reasoning applies to the current results with two-digit numbers being perceptually simpler than words that were three to eight letters long. Also, participants only needed to process the last digit to complete the numeric categorization task, but they had to process the entire word to complete the verbal categorization task.

Dark and Benbow (1991) found that girls were faster than boys in a lexical-decision task, a task also assumed to reflect verbal encoding and decision speed. The current data showed no sex difference. The conflicting pattern could reflect either the difference in sample characteristics (precocious youth versus extremely precocious youth) or the difference in the type of decision (categorical versus lexical). A rationale for the latter explanation is described in the section on correlations.

Dual-Task Recall. Because of a programming error, the recall data for the first 18 participants were not recorded; therefore, the analyses of dual-task recall are based on data from 86 participants (37 girls and 49 boys). The recall data were scored in an all-or-none manner: A list was counted as correct only if all five items were recalled in their proper order. The proportions of correctly recalled digit and word lists are shown in the middle panel of Table 2. A 2 × 2 ANOVA with type of list as a within-subjects variable and sex as a between-subjects variable showed a main effect of type of list, $F(1, 84) = 270.02$, $MSE = .021$: More of the digit lists were recalled. There were no reliable effects involving sex.

Better recall of digits than words was expected on the basis of prior research (Brown & Kirsner, 1980; Case, Kurland, & Goldberg, 1982; Dark & Benbow, 1991; Puckett & Kausler, 1984). An ANOVA performed on the verbal categorization latencies also suggested that digit lists were easier to handle than word lists. There was a main effect of type of list, $F(1, 84) = 92.60$, $MSE = 10{,}138$, with faster categorizations when digits were in memory ($M = 893$ ms; $SE = 20$) than when words were in memory ($M = 1{,}045$ ms; $SE = 25$). There were no reliable effects involving sex.

Continuous Paired Associates. Proportion correct in the continuous paired-associate task is shown in the bottom panel of Table 2 for both word and digit responses as a function of sex. An ANOVA with sex and type of response as variables showed no reliable differences. The stimuli were comparable in that both the word and digit responses were selected randomly from a set of 10 alternatives. Although the words were high in imagery and concreteness, they did not appear to be easier to associate to the letters than digits.

Correlations With SAT

Although the differences in working-memory performance with the two types of stimuli are of interest, and especially of interest is the lack of a sex difference for each task, the main question addressed by the current research concerned the relationship between working-memory performance and precocity. Specifically of interest was the extent to which mathematical and verbal precocity, as reflected in high SAT-M and SAT-V scores earned by age 13, were differentially related to working-memory performance as a function of type of stimulus. We begin to address this issue here. This section describes the relationships in terms of simple correlations between performance and SAT scores. In addition to the correlations computed from the total sample data, separate correlations were computed for each sex and the magnitude of the correlations compared. Only when the comparison suggested that the relationship might be different for boys and girls are the correlations by sex discussed in the text. This seemed to be the more reasonable approach given the lack of sex differences in the data themselves.

Because the direction of all correlations between numeric stimuli and SAT-M scores and between verbal stimuli and SAT-V scores was predicted in advance, their reliability was assessed via one-tailed tests. The reliability of other correlations was assessed via two-tailed tests. A pattern showing reliable correlations between SAT-M score and performance with numeric stimuli, but not with verbal stimuli, and a pattern showing reliable correlations between SAT-V score and performance with verbal stimuli, but not with numeric stimuli, would confirm directly the differential relationship between type of ability and type of stimulus in working-memory tasks.

Specific hypotheses concerning the differential relationship between precocity and type of stimulus also were tested via one-tailed tests using a formula designed to handle correlations obtained from correlated samples (Ferguson, 1966). First, the relationship was tested within each type of precocity. For both SAT-M and SAT-V score there was a direct comparison between the correlation with verbal versus numeric stimuli for each working-memory task: The prediction with SAT-M score was that the correlation would be larger with numeric stimuli than with verbal stimuli and the prediction with SAT-V score was that the correlation would be larger with verbal stimuli than with numeric stimuli. Second, the relationship was tested within each type of stimulus. For each specific measure there was a direct comparison between the correlation with SAT-M score versus SAT-V score: The prediction with numeric stimuli was that the correlation with SAT-M score would be larger than with SAT-V score, and the prediction with verbal stimuli was that the correlation with SAT-V score would be larger than with SAT-M score.

Categorization Latency. The simple correlations between categorization latency with each type of stimulus and SAT-M and SAT-V scores are shown in Table 3 for the total group and by sex. The correlation between numeric categorization latency and mathematical precocity, as measured by SAT-M score, was negative and reliable; that is, higher SAT-M scores were associated with faster latencies. None of the correlations between SAT-M scores and verbal categoriza-

TABLE 3
Simple Correlations Between SAT Scores and the Working-Memory Tasks for Girls and Boys and the Total Sample

Type of Stimulus	SAT-M			SAT-V		
Measure	Total	Girls	Boys	Total	Girls	Boys
Numeric Stimuli						
Categorization latency[a]	−.33*	−.27*	−.32*	.17	.19	.14
Dual-task recall[b]	.31*	.53*	.26*	.09	.32*	−.08
Recall in CPA[a,c]	.27*	.34*	.31*	.11	−.01	.19
Verbal Stimuli						
Categorization latency[a]	−.10	−.08	−.10	−.12	−.07	−.15
Dual-task recall[b]	.19	.25	.25	.23*	.18	.24*
Recall in CPA[a,c]	.24*	.18	.38*	.21*	.14	.24*

Note. SAT-M = Scholastic Aptitude Test, mathematical ability score; SAT-V = Scholastic Aptitude Test, verbal ability score.

[a] There were 43 girls and 61 boys. [b] There were 37 girls and 49 boys. [c] CPA = continuous paired associates.

*$p < .05$

tion latency was reliable. Dark and Benbow (1993) also reported a relationship between mathematical precocity and the decision that digits were mismatching. The numeric categorization data confirm the relationship between digit encoding speed and mathematical precocity.

There was no reliable correlation between numeric categorization latency and verbal precocity, as measured by SAT-V score, but none was expected. A reliable negative correlation was expected, however, between verbal categorization latency and verbal precocity. Although the correlation was negative in sign, it was not reliable. Dark and Benbow (1991) found faster decision times for extremely verbally precocious participants in a lexical-decision task, but the ability differences were not apparent when sex was included as a variable in the analysis. Dark and Benbow (1993) found support for a relationship between extreme verbal precocity and decisions about mismatching verbal stimuli, but sex was not included in their analysis. Neither sex showed a reliable relationship between verbal categorization and verbal precocity in the current research.

The direct comparisons confirmed the pattern for numeric stimuli and for SAT-M score that was found with simple correlations: Numeric categorization latency was more strongly correlated with SAT-M than was verbal categorization latency, $t(101) = 2.56$, $SE = 1.132$, and numeric categorization latency was more strongly correlated with SAT-M score than with SAT-V score, $t(101) = 4.28$, $SE = 1.278$. There was no reliable difference in the correlation between verbal categorization latency and SAT-V score versus SAT-M score, confirming the pattern of no reliable simple correlations. Although none of the simple correlations involving SAT-V score was reliable, the direct comparison showed a reliable difference in the correlation between SAT-V score and verbal versus numeric categorization latency, $t(101) = 3.09$, $SE = 1.152$. This finding suggests that the difference in the direction of the correlations is reliable; that is, faster verbal categorization latency is associated with higher SAT-V score, and faster numeric categorization latency is associated with lower SAT-V score. The former is predicted on the basis of our prior research, but there is no basis for predicting the latter.[3] Given that neither simple correlation was reliably different from zero, we consider this finding very tentative.

As already noted, response latency in the categorization tasks reflects both encoding speed and decision speed. A post hoc consideration of the verbal-categorization task suggested that it may be more purely an encoding task than the tasks used in earlier research. The categorization task required a decision about the semantic category of a concrete noun that referred to a typical instance of the category. Encoding of such stimuli is likely to include automatic activation of the category label. In other words, it is possible that the verbal-categorization task can be performed entirely within the lexical system because the correct response is part of the encoded representation of the stimulus. On the other hand, decisions about lexicality and about a match between two stimuli have to be derived from the encoded representations by a mechanism outside the lexical system (cf. Besner, 1990). Thus, the relationship between verbal precocity (or sex) and latency found in the earlier studies may have reflected the decisions about the encoded representation rather than the encoding process itself.

Consideration of the numeric-categorization task from a similar post hoc perspective suggested that the decision as to whether a two-digit number is odd or even requires postencoding processing in the same way that the match–mismatch task and the lexical-decision task do. That is, a decision about the property of odd or even for two-digit numbers must be derived from the encoded long-term memory representation. Clearly, further research is needed to determine whether encoding or postencoding decision processes for both numeric and verbal stimuli are related to precocity (cf. Whitney et al., 1990).

Dual-Task Recall. The correlations between SAT-M scores and dual-task recall of digits and between SAT-V and dual-task recall of words were positive and reliable. The correlation between SAT-M scores and dual-task recall of words, however, also was positive and was marginally reliable, $p = .08$ (two-tailed). As with categorization latency, the direct comparisons for numeric stimuli and SAT-M score confirmed the pattern found with the simple correlations: Although there was no reliable difference in the correlations between SAT-M score and numeric

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[3] The correlation between SAT-V score and numeric categorization accuracy was .07 and the correlation between SAT-V score and verbal categorization accuracy was .18. Thus, there was no indication of a speed–accuracy trade-off.

versus verbal dual-task recall, numeric dual-task recall was more strongly correlated with SAT-M score than with SAT-V score, $t(83) = 1.68$, $SE = 1.325$. As would be expected from the simple correlations, there was no reliable difference in the direct comparison between verbal dual-task recall and SAT-V score versus SAT-M score. Although the simple correlations showed that SAT-V score was reliably related to dual-task recall of words but not digits, the difference was not confirmed in the direct comparison.

The correlations between ability and recall of items "matching" the type of precocity were expected from the results of Dark and Benbow (1990, 1991) showing that higher digit span was related to mathematical precocity and higher word span was related to verbal precocity. The fact that the correlation between word memory and SAT-M scores also was positive and marginally reliable suggests that more than just working-memory storage capacity is reflected in recall under dual-task conditions. It is likely that dual-task recall reflects not only working-memory capacity, but also the ability to maintain and manipulate information in working memory, an ability associated with mathematical precocity (Dark & Benbow, 1990, 1991; Hunt et al., 1973).

The comparison between the sexes for the correlation between dual-task recall of digits and SAT-V yielded a marginally reliable difference, $p = .07$. The correlation was positive and reliable for girls but not for boys. This finding must be replicated before it is given further consideration.

Continuous Paired Associates. As expected on the basis of prior research (Dark & Benbow, 1990, 1991; Hunt et al., 1973), digit recall in the continuous paired-associates task correlated positively and reliably with SAT-M scores. Digit recall in the continuous paired-associate task was not related to SAT-V score for any group. Of particular interest were the correlations between word recall in the continuous paired-associates task and both SAT-M scores and SAT-V scores. Both correlations were positive and reliable. None of the direct comparisons between the correlations showed a reliable difference, but the only difference that would be expected on the basis of the simple correlations was between verbal and numeric stimuli for SAT-V score.

Better performance in the continuous paired-associates task, which requires formation and updating of temporary associations in working memory, previously has been associated with higher mathematical ability when numbers are used as responses (Dark & Benbow, 1990, 1991; Hunt et al., 1973). The current data confirm that finding and show that the relationship holds for both sexes. A positive relationship with mathematical ability also has been shown when letters and locations are used as responses (Dark & Benbow, 1990, 1991). The current research extends the finding to include words. It appears, though, that performance with words also is related to verbal precocity. To the extent that compactness of a representation makes forming and maintaining an association easier, one would expect better performance with word stimuli for verbally precocious participants even if the operations underlying the task itself were more closely related to mathematical precocity.

Prediction of SAT Score by Type of Stimulus

The correlations described in the previous section show the relationship between SAT scores and separate measures of working-memory performance. SAT-M scores were reliably correlated with all three numeric measures and SAT-V scores were reliably correlated with two of the verbal measures. Each measure was designed to tap into a different component of working memory. Thus, the measures could be correlated with different aspects of the abilities reflected in the SAT and combinations of measures might predict SAT scores better. For example, Cantor et al. (1991) found evidence that the storage capacity of working memory and what might be called the operation capacity independently contributed to the prediction of ability. This possibility was examined here by using stepwise multiple regression. Numeric measures were used as predictors of SAT-M scores and verbal measures were used as predictors of SAT-V scores. Because there were no gender differences in the correlational analyses, the regressions were computed only for the total group. The beta weights and multiple *R* values associated with each regression are shown in Table 4.

All three numeric measures contributed to the prediction of SAT-M, $R = .47$, $F(3, 82) = 7.92$, $MSE = 7{,}391$. Numeric categorization latency (assumed to reflect stimulus encoding speed) was the first variable entered; digit recall after verbal categorization (assumed to reflect working-memory storage capacity) was the second variable chosen, and digit recall in continuous paired associates (assumed to reflect manipulation via association formation) was the third variable chosen. Each of the working-memory tasks contributed to the prediction of SAT-M scores; together they accounted for 22% of the variation in SAT-M scores. Although it is possible that components of the tasks that are unrelated to working memory are responsible for the separate contributions, the regression results fit

TABLE 4

Beta Weight, Multiple R, R^2, and Change in Multiple R^2 Associated With Each Variable in the Stepwise Regressions

	Beta	Multiple *R*	R^2	Change in R^2
Predicting SAT-M Score				
Numeric categorization latency	−.28	.32	.10	.10
Dual-task recall—Digits	.26	.43	.19	.09
Recall in CPA[a]—Digits	.20	.47	.22	.04
Predicting SAT-V Score				
Dual-task recall—Words	.23	.23	.05	.05

Note. The *F* to enter a variable in the stepwise regression was 3.9 and the *F* to remove was 3.8.
[a]CPA = continuous paired associates.

well with our assumptions. That is, the regression results are compatible with the suggestion that the working-memory measures were indeed tapping different aspects of working memory and that the different aspects contributed separately to prediction of SAT-M scores.

Only dual-task word recall contributed to the prediction of SAT-V with the verbal stimuli, $F(1, 84) = 4.48$, $MSE = 7{,}772$. Although word recall in the continuous paired-associate task showed a reliable correlation with SAT-V score, it did not add to the prediction of SAT-V score in the stepwise regression equation. Earlier, we suggested that both the correlation between SAT-V score and dual-task word recall and the correlation between SAT-V score and continuous paired-associate recall were due to the compactness of the verbal representations. The fact that only one of the measures was included in the stepwise regression is consistent with that assertion.

The regression results also further support what is suggested by the correlations alone: SAT-M scores are more strongly related to performance on at least some working-memory tasks than are SAT-V scores. The current data suggest that SAT-M scores are related to measures of both storage and operations, whereas SAT-V scores are related only to storage.

General Discussion

The current research was designed to more fully explore the relationship between components of working memory and precocity as a function of type of stimulus. Encoding and decision speed, measured via categorization latency, was investigated first. Mathematical precocity was related to speed in a numeric categorization task, whereas speed in a verbal task was not related to either type of precocity. The finding that precocity was differentially related to speed as a function of type of stimulus means that neither mathematical nor verbal precocity is related to encoding and decision speed per se. The type of encoding and the type of decision seem to be the important factors.

Working-memory capacity, measured in terms of accuracy of dual-task recall, also was studied. The data showed an overall difference as a function of type of stimulus (i.e., digit lists were easier to recall than word lists). The most important finding, however, concerned differences in handling types of stimuli as a function of type of precocity. The ability to remember digit lists was related more strongly to mathematical precocity than to verbal precocity. The relationship between precocity and memory for word lists was less clear-cut. Although word memory was reliably correlated with verbal precocity, the relationship with mathematical precocity also was found to be marginally reliable. We suggest, given previous and current findings, that the relationship with verbal precocity reflected stimulus-specific differences in storage capacity and that the relationship with mathematical precocity reflected a more general difference in the ability to manipulate information in working memory (coordination of two tasks in this case).

The ability to manipulate information in working memory also was measured more directly via recall in the continuous paired-associates task. There was no overall difference in performance between words and digits in the task. The relationship between paired-associate digit recall and mathematical precocity reported in earlier studies (Dark & Benbow, 1990, 1991; Hunt et al., 1973) was confirmed yet again for both boys and girls. Manipulation of digit information in memory appears to be a stable characteristic of mathematically precocious youth. Continuous paired-associate performance with words was reliably related to both mathematical and verbal precocity. We interpret the results as showing that mathematical precocity is related to manipulation of information in working memory, regardless of stimulus type, but that more compact representations are also easier to manipulate. Thus, task performance is enhanced in the verbally precocious because their verbal representations are more compact.

Taken as a whole (Dark & Benbow, 1990, 1991, 1993, this study), our data support the assertions that working-memory operations (like forming and updating associations or coordinating two tasks at once) are more closely related to mathematical precocity than verbal precocity, and that there are differences in the compactness with which verbal and numeric stimuli are represented for verbally and mathematically precocious youth. Our appeal to the compactness of representations for the latter findings reflects our belief that there are differences in how verbal and numeric information are represented in long-term memory for verbally and mathematically precocious youth (Dark & Benbow, 1990, 1991). That is, we attribute the type of stimulus effects to differences in the nature of the representation rather than to the existence of separate working memories for each type of stimulus, an alternative suggested by Monsell (1984), who also acknowledged that individual differences in working memory could differ as a function of stimulus type. Compactness could, however, reflect differences in the efficiency with which the information is handled in working memory rather than differences in long-term memory representations. Working-memory efficiency and long-term memory compactness are not distinguishable with extant empirical data.

Our data, however, can shed light on the question of whether the relationship between working-memory capacity and ability reflects individual differences in capacity per se or differences in the efficiency of processing. Some researchers have suggested that the relationship reflects differences in the efficiency of working-memory processing (e.g., Das & Sui, 1989; Larson, Merritt, & Williams, 1988; Larson & Saccuzzo, 1989). Persons who process efficiently can make the same amount of limited-capacity resources go further. Others have suggested that ability is related to differences in the overall capacity of working memory, with higher ability associated with larger capacity (e.g., Cantor & Engle, 1993; Engle, Cantor, & Carullo, 1992; Just & Carpenter, 1992). Although, as pointed out by Just and Carpenter (1992), the capacity and efficiency explanations of the relationship between ability and working memory are not mutually exclusive (i.e., both could be true), our data showing differences in stimulus compactness are consistent with an explanation in terms of differences in processing efficiency (and/or differences in the underlying long-term memory representations) as a function of type of talent. At least among the precocious youth included in our research, it does not seem to be the case that verbal ability is associated with a difference in the overall capacity of working memory. Mathematical precocity, however, is related to the ability to manipulate information in working memory.

We now consider further how our conclusion that a more capable working memory is related to mathematical precocity fits with the conclusion of a large literature that working-memory capacity is related to *verbal* comprehension (e.g., Cantor et al., 1991; Daneman & Carpenter, 1980; Das & Sui, 1989; Engle et al., 1992; Just & Carpenter, 1992; La Pointe & Engle, 1990; Turner & Engle, 1989), two seemingly contradictory claims. But are they actually in conflict? We believe that the answer is no. Working-memory capacity has almost always been measured via reading span (Cantor et al., 1991; Daneman & Carpenter, 1980; Engle et al., 1992; Just & Carpenter, 1992; La Pointe & Engle, 1990; Turner & Engle, 1989), operations span (Engle et al., 1992; La Pointe & Engle, 1990; Turner & Engle, 1989), or simple span (Cantor et al., 1991; Das & Sui, 1989; Engle et al., 1992; La Pointe & Engle, 1990) for *words* but not digits (although Cantor et al., 1991, did find that digit reading span predicted reading comprehension). Thus, working-memory capacity has been measured with verbal and not numeric stimuli, thereby giving the verbally precocious an advantage due to the compactness of their verbal representations. Indeed, our own data do show that word span predicts verbal precocity. The apparent conflict between our data and the comprehension literature results because the comprehension literature draws conclusions about overall working-memory capacity from data on working-memory capacity for verbal stimuli only. We think this is misleading.

Moreover, the comprehension literature examines verbal comprehension in a general population, often relying on samples of college students. The relationship between span tasks, using verbal stimuli, and mathematical ability often is not even assessed. In addition, our data examine differences between verbally and mathematically precocious youth, with the focus on differences as a function of type of precocity. Further, it is not clear to us that it would be easy to assess in a college population the same type of reasoning ability that defines mathematical precocity in our samples. Although we define precocity in terms of SAT-M score, it is important to remember that the youth taking the SAT have not yet had algebra. In our sample, SAT-M scores reflect reasoning more strongly than training (Benbow & Stanley, 1981, 1983). Thus, training would more heavily influence scores in a college population in comparison to ours.

In sum, using simple information-processing tasks designed to assess the "mechanistic aspects of thought" (Hunt, 1978, 1983), not only have we been able to identify variables associated with performance on complex ability tasks, but also to reveal some of the simple processes associated with mathematical and verbal precocity (Dark & Benbow, 1990, 1991, 1993, this study). Mathematically and verbally precocious youth seem to excel in different mechanistic aspects of thought. Our interpretation of the data is that verbal stimuli are more compactly represented in the verbally precocious than in the mathematically precocious, with the opposite pattern for numeric stimuli. Thus, storage capacity of working memory is stimulus specific. Yet the ability to manipulate information in working memory is related to mathematical precocity, irrespective of stimulus type. This is an interesting finding, given the close correspondence between mathematical reasoning ability as operationalized in this study and fluid intelligence. Now we need to determine what mechanistic process of thought, if any, is closely aligned with verbal precocity, a good proxy for high levels of crystallized intelligence. Our earlier, but preliminary, work seems to identify some aspect of long-term memory with our current research suggesting it is not in the encoding aspect.

We end with a comment about a limitation of the cognitive correlates approach. Cognitive correlates research can identify relationships between simple and complex tasks, but whether the relationships are causal and, if so, the direction of the causality, cannot be determined. Thus, our research does not allow us to say either that differences in compactness of representations cause differences in precocity or that differences in precocity cause differences in the compactness of representations. Research using other paradigms will be needed to answer such questions (see, for example, Wadsworth, DeFries, Pennington, & Olson, 1992). Determining what the relationships are, however, is a necessary first step in determining the causal nature of the relationship. Our work is part of this first step.

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