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Ability Factors and Cognitive Processes*

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Several measures of the speed of information processing were related to ability factors derived from the Cattell-Horn theory of fluid and crystallized intelligence. Ninety-one college students took a battery of paper and pencil tests designed to measure four ability factors: fluid intelligence (Gf), crystallized intelligence (Gc), spatial visualization (Gv), and clerical perceptual speed (CPS). They also performed paper and pencil and computerized versions of three information processing tasks: mental rotations, letter matching, and sentence verification. Correlations among the ability measures, among the information processing measures, and between the two domains were analyzed using confirmatory factor analysis. The four ability factors were found to be largely independent in this college population. Speed of letter-matching and sentence verification were highly correlated, but neither was related to speed of mental rotation. Mental rotation speed was strongly correlated with Gv; letter matching speed was correlated with CPS; and sentence verification speed was correlated with both Gc and CPS.

During the past decade there have been numerous attempts to relate the cognitive abilities measured by psychometric tests to the information processing functions observed in paradigms devised by experimental psychologists (Carroll & Maxwell, 1979). One of the methods used to achieve this goal is the "cognitive correlates" approach (Pellegrino & Glaser, 1979), in which psychometric test performance is correlated with performance on one or more information processing tasks. Typically these tasks are chosen because they are regarded as pure tests of cognitive processes. The psychometric tests used are often quite broadly defined. Consider, for instance, studies in which "verbal intelligence" has been correlated with performance on an experimental test battery (Hogaboam & Pellegrino, 1978; Hunt, Davidson, & Lansman, 1981; Hunt, Lunneborg & Lewis, 1975). In this situation, relatively fine measures derived from one theoretical approach to cognition are compared to broader based measures developed from another theoretical tradition. An obvious refinement is to choose psychometric tests that will measure

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particular, theory-based ability factors. Here we report an experiment that extends the cognitive correlates approach, by relating information processing performance to the finer measures derived from a detailed psychometric theory: the theory of fluid and crystallized intelligence, proposed by Cattell (1941, 1963) and amplified by Horn (1968, 1978; Horn & Cattell, 1966; Horn & Donaldson, 1980).

A second purpose of the current study was to determine the extent to which method factors may have contaminated previous studies using the cognitive correlates design. Group psychometric tests almost always use the familiar paper and pencil format. The information processing tasks developed by experimental psychologists use fairly elaborate apparatus for presenting stimuli and measuring responses to them. The theoretical conclusions that are drawn by both psychometricians and experimental psychologists are clearly not intended to be specific to the experimental situation, but it is certainly true that some unknown percentage of the variance in performance in each situation is due to individual reactions to the testing situation itself. If these apparatus factors are not highly correlated, then the simple correlations between psychometric test performance and information processing speed will underestimate the correlation between the abilities tested within each format. In the experiment reported here, we developed conventional (i.e., reaction time) tests and paper and pencil tests to tap the same cognitive processes. Method-free process factors were derived from the information processing tests, and these factors were then correlated with the psychometric ability factors. As a subsidiary outcome of this design, we were able to estimate the validity of paper and pencil tests as measures of cognitive processes that have conventionally been defined by performance in reaction time paradigms. Since paper and pencil measures are much cheaper to obtain than reaction time measures, this aspect of the study may have some practical value in applied research.

Choice Of Psychometric Tests

Four factors were chosen from the Cattell-Horn theory as potential correlates of information processing ability. Crystallized intelligence (Gc) and fluid intelligence (Gf) emerge as factors when measures of more specific primary mental abilities are factor analyzed (Horn & Cattell, 1966; Horn & Donaldson, 1980). Gc is associated with education and general acculturation, especially as they pertain to the use of language. Tests of vocabulary and general information typically load highly on the Gc factor. Gf is associated with the ability to use complex reasoning to deal with problems for which subjects must develop their own strategies. Examples of tests loading on the Gf factor are the Raven Progressive Matrices Test and Thurstone's Letter Series Completion Test, variants of which were used in this experiment.

In addition, the Cattell-Horn theory recognizes the existence of a modality specific ability to manipulate visual stimuli. This factor has been labelled "spatial visualization" (Gv) and bears a close relationship to the spatial ability factor posited by a number of other psychometric theories. The existence of a distinct spatial ability factor has been established in numerous studies of intelligence (Nunnally, 1978; Willerman, 1979), and has received added support from research on hemispheric specialization and sex differences. Tests loading on Gv include Formboard, Paperfolding, and Figures tests.

Another ability recognized by the Horn-Cattell theory is the ability to recognize accurately the minor details of visual stimuli without regard to their meaning. This ability is identified as "Clerical and Perceptual Speed" (CPS). Roughly, the distinction between Gc and CPS parallels the distinction between reading for content and proof reading. Since several information processing tasks require rapid responses to simple visual stimuli, it seemed possible that speed on these tasks would be related to clerical ability. In order to allow for this possibility, tests of CPS were included in the psychometric test battery.

Information Processing Measures

The information processing measures used in this study were based on three experimental tasks: mental rotations (Shepard & Metzler, 1971), letter-matching (Posner & Mitchell, 1967), and sentence verification (Clark & Chase, 1972). These tasks were chosen for several reasons. First, they seem to draw upon different types of information processing skills. Second, each has been studied extensively by experimental psychologists, and fairly detailed models have been proposed to explain performance on the tasks. Third, individual differences on each task have been shown to be related to psychometric ability measures.

Mental Rotations. Sample stimuli for the mental rotations task are shown in Figure 1. On each trial, the subject was asked to determine whether two drawings of three-dimensional block figures represented the same object. Shepard and Metzler (1971) found that RT to make a "same" response was a linear function of the angular disparity between the two figures. They also found that the function relating RT to angular disparity was almost identical whether rotation was in the picture plane around an axis perpendicular to the figure, as in Figure 1a, or "in depth" around a vertical axis, as in Figure 1b. They concluded that subjects solved the problems by mentally rotating one of the objects into congruence with the other. According to their model, the slope of the function relating RT to angular disparity indicates the speed of mental rotation. The intercept represents the speed of processes common to all angular disparity conditions, e.g., encoding, decision, and keypressing. While this model has been challenged (Carpenter & Just, 1976; Yuille & Steiger, 1979), alternative models all agree that the slope of the RT function in the mental rotations task is an indicant of efficiency of processing the visual image.

Individual performance on the mental rotations task has been related to measures of spatial ability. Snyder (1972) compared subjects of low and high spatial

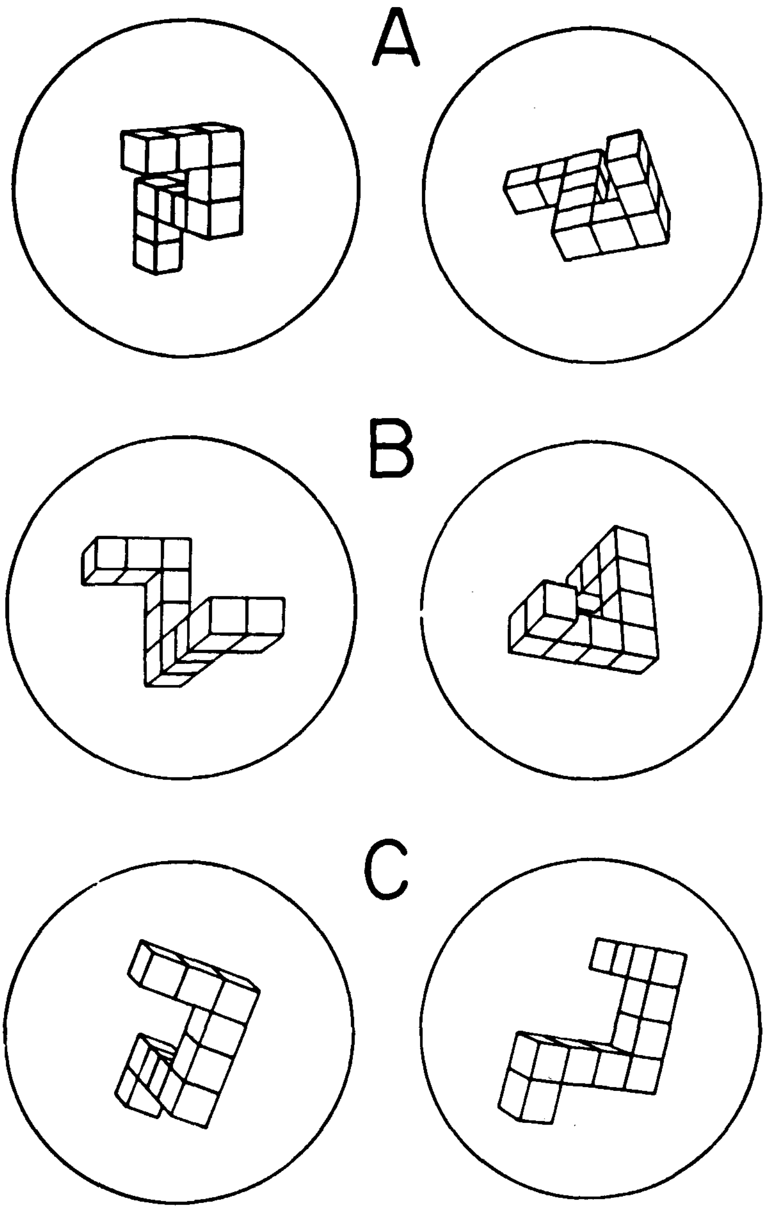

FIG. 1. Sample stimuli from the Shepard and Metzler (1971) mental rotations task: a) same, picture plane rotation; b) same depth rotation; c) different.

ability in their performance on picture plane rotations. He found that the slope of the function relating RT to angular disparity was steeper for low than high-ability subjects. Tapley and Bryden (1977), using only depth rotations, correlated performance on the mental rotations task with two paper and pencil tests of spatial ability. They found that intercepts, slopes and accuracy were related to the spatial ability measures. In neither of these studies were measures of non-spatial abilities available, so it was not possible to determine whether the correlations between task parameters and ability measures were specific to spatial ability or whether they reflected general cognitive ability.

Letter-Matching. One of the most heavily investigated tasks in the cognitive literature is the letter-matching task, introduced by Posner and Mitchell in 1967. They found that if subjects are asked to decide whether two letters are the same or different, the response is faster if the match can be made on the basis of physical identity (e.g., A A) than if it must be made on the basis of the names of the letters (e.g., A a). Posner's explanation for this finding rests on his belief that presentation of a stimulus automatically activates several types of internal codes (Posner, 1978). In the case of a letter, codes representing both the physical nature of the stimulus and its name are activated. The physical match can be made on the basis of either the physical or the name code, but the name match is dependent on the name code alone.

Hunt (1978) has argued that speed of making the name match, relative to speed of making the physical match, should represent the subject's facility in accessing the name of a symbol. He found that the difference between RT to make a name match (NI) and RT to make a physical match (PI) was correlated with verbal ability as measured by a college entrance examination (r about $-.3$) (Hunt, 1978). This finding has been replicated by Jackson and McClelland (1979), who found that time to make a name match correlated more highly with reading efficiency than any of the other information processing measures they studied.

In the present research, we hoped to answer some more specific questions concerning the relationship between letter-matching measures and particular ability dimensions. For example, Hunt has argued that letter-matching speed reflects speed of access to well-learned codes in long-term memory. In contrast, Hogaboam and Pellegrino (1978) have suggested that letter-matching speed may reflect ability to handle a novel problem that is unrelated to everyday use of language. If Hogaboam and Pellegrino are right, then letter-matching RT should be more highly correlated with Gf than with Gc. On the other hand, if letter-matching speed reflects overall familiarity with written language, then it should be more highly correlated with Gc. A third possibility is that letter-matching speed is more highly related to the speed factor, CPS, than to either Gc or Gf.

Sentence Verification. Another verbal task that has been the object of extensive research by cognitive psychologists is the sentence verification task. In this task, the subject is asked to determine if a sentence, such as "Plus is above star," is a true description of a picture, in which a plus is shown either above or below a star. Like letter-matching, sentence verification involves processing of highly over-learned verbal symbols. Neither task differentiates between college students on the basis of "knowledge," in the usual sense of the word, since all literate adults know the meanings of all the symbols required to do the tasks. However, since sentence verification requires subjects to integrate the meanings of the words in a sentence, it represents a more complex form of verbal processing than letter-matching. We and others have found that overall RT in the sentence verification task is correlated with general measures of ability. Lansman (1978) reviewed a number of studies conducted in our laboratory in which the correlation between verbal ability and RT in various sentence verification paradigms varied from −.32 to −.58. Baddeley (1968) found that scores on a 3-minute paper and pencil version of a sentence verification task correlated quite highly ($r = .59$) with performance on the British Army verbal intelligence test.

Analyses of sentence verification RTs can provide parameter estimates that are related to theoretical models of how people perform the task. The most common models assume that subjects encode both sentence and picture into verbal propositions, then compare the two propositions (Carpenter & Just, 1975; Clark & Chase, 1972). According to Clark and Chase (1972), RT in the sentence verification task can be broken down into four independent parameters: (a) a base time reflecting response and decision parameters common to all types of trials; (b) negation time, the added time necessary to encode and process negatively stated sentences (e.g., Plus is not above star) as compared to positively stated sentences (e.g., Plus is above star); (c) falsification time, time to change the "truth marker" that indicates whether sentence and picture propositions match; and (d) added time necessary to process the marked preposition "below" as opposed to the unmarked preposition "above." Carpenter and Just (1975) developed a more parsimonious model for the sentence verification task in which negation time and falsification time both result from repetitions of the same basic comparison process. Both models predict the same ordering of RTs for the four basic sentence-picture combinations.

In the present study, subjects were administered a battery of psychometric tests chosen to define the four ability factors: Gf, Gc, Gv, and CPS. They also performed computerized and paper and pencil versions of the three information processing tasks, mental rotations, letter-matching, and sentence verification. Patterns of individual differences within the experimental tasks, between paper and pencil and computerized versions of the same task, and between experimental and psychometric tests were analyzed.[1]

[1]Recently, MacLeod, Hunt, and Mathews (1978) found that when sentence and picture were presented sequentially in the sentence verification paradigm, two strategies were possible. The "linguistic strategy" resembled the models proposed by Carpenter and Just and Clark and Chase; the subject encoded both sentence and picture into propositional form and compared the two propositions. However, a small number of subjects seemed to use a "spatial strategy," in which the sentence is encoded

METHOD

Subjects

Forty-five male and 46 female freshmen and sophomores at the University of Washington served as subjects. They were selected on the basis of spatial ability. Most Washington State high school students who plan to apply for admission to the University of Washington take the Washington Pre-College Test Battery during eleventh grade. This battery includes a test of spatial ability that requires the student to specify which of several three-dimensional objects could be formed by mentally "folding up" a given two-dimensional figure. Selection of subjects was based on the distributions of scores on the spatial test for males and females who entered the University of Washington as freshmen in 1973. The distribution for each sex was divided into sixths. Seven subjects were recruited from each sixth of the male and female distributions.

Subjects participated in 10 1-hour sessions on consecutive week days. They were paid $3.00 per hour for their participation. During the first four sessions, paper and pencil tests were administered.[2]

Apparatus

In all computer-controlled tasks, presentation of stimuli and recording of responses were under the control of a Data General Corporation NOVA 3 computer. Stimuli for the letter-matching and sentence verification tasks were presented on independently controlled Tektronix 604 cathode ray oscilloscopes. Stimuli for the Mental Rotations Task were rear projected by a Kodak Carousal Slide Projector onto 20 by 20 cm screens. In each case, the subject responded on the right-most and left-most of a set of eight response keys. One to six subjects were run simultaneously but asynchronously in separate, sound-proofed booths.

Procedure

The paper and pencil tests were administered during the first four sessions and at the end of the sixth session. The computerized testing took place during Sessions 5–10. The order of presentation of the tests is shown in Table 1.

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as a mental image and the picture is compared to this image. MacLeod et al. found that among subjects who used the linguistic strategy, sentence verification RT was correlated with verbal ability, whereas among subjects who used the spatial strategy, verification time was correlated with spatial ability.

In this study, we wanted to avoid the differences in strategy so that parameters would reflect the same processes for all subjects. Therefore, in the computerized version of the task, we presented sentence and picture simultaneously, hoping that this would encourage all subjects to use a linguistic strategy.

[2]Men and women were selected according to their position in the distribution of spatial ability scores for their own sex so that we could analyze the data for sex differences on the mental rotations task. Analyses of sex differences in these data have been reported by Glascock (1979).

TABLE 1
Order of Administration of Paper and Pencil and Computerized Measures

	Name	Task
Day 1:	Letter-Matching (Paper and pencil version)	Determine which pairs of letters have the same name.
	Sentence Verification (Paper and pencil version)	Determine which simple sentences are true descriptions of the accompaying pictures.
	Mental Rotations (Paper and pencil version)	Determine if two three-dimensional figures can be rotated into congruence.
	Figure Identity	Determine if two closed line figures are identical in shape.
	Hidden Patterns	Mark the line figures in which a given line model is embedded.
Day 2:	Cards	Choose the two-dimensional figures which can be rotated into congruence with the model.
	Simple Analogies	Solve analogies involving difficult words and simple relationships.
	Esoteric Analogies	Solve analogies involving simple words but complex relationships.
	Form Board	Mark the shapes which could be put together to form a model shape.
	Finding A's	Cross out the words that contain an "A."
	Letter Series	Determine what letter logically follows in a systematic sequence.
Day 3:	Cube Comparisons	Determine if two pictures represent the same alphabet block.
	Vocabulary	Choose the correct definition of a given word.
	Identical Pictures	Choose the picture that is identical to the model.
	General Information	Answer a broad variety of multiple choice questions of general information.
	Matrices	Choose the picture which logically completes a 2×2 matrix of pictures.
	Remote Associations	Produce a word that is related to three given words.
	Figures	Mark the two-dimensional line drawings that can be rotated into congruence with the model.
Day 4:	Mental Rotations (Paper and pencil version)	Determine if two three-dimensional figures can be rotated in congruence.
Day 5:	Computerized Letter-Matching Task	
Day 6:	Computerized Sentence Verification Task	

TABLE 1 (*continued*)

	Name	Task
Day 6:	Paper Folding	After observing how a sheet of paper has been folded and punched, choose the picture that shows how the paper would look when unfolded.
	Cancelling Numbers	Determine if two seven digit numbers are identical.
Days 7, 8, 9, 10:	Computerized Mental Rotations Task	

The experimental procedures for the computerized versions of the letter-matching and sentence verification tasks were similar. In each case, a warning dot appeared in the center of the screen for 500 msec at the beginning of each trial, followed immediately by the stimulus for that trial. If the subject responded correctly to the stimulus the reaction time was displayed on the screen. If the subject responded incorrectly, the word "Wrong" appeared. The feedback message was displayed for 500 msec, followed by a 500 msec inter-trial interval.

Letter-Matching Task. The stimuli were pairs of letters. On one-fourth of the trials, the two letters were physically identical (e.g., AA); on one-fourth they were identical in name but not in shape (e.g., Aa); and on the remaining half they differed in name as well as shape. Subjects pressed a key on the right if the letters had the same name, and a key on the left if they had different names. There were four blocks of 96 trials each.

Sentence-Verification Task. The stimuli consisted of a sentence and a picture of the form, "PLUS ABOVE STAR $\overset{+}{*}$ or "STAR NOT BELOW PLUS $\overset{*}{+}$." Sixteen possible sentence-picture combinations were formed by the factorial combination of PLUS or STAR as subject; IS or IS NOT; ABOVE or BELOW; and $\overset{*}{+}$ or $\overset{+}{*}$. Since each sentence-picture combination was displayed equally often, half of the sentences were affirmatively stated and half were negatively stated, half were true and half were false.

The subject's task was to decide if the sentence was a true description of the picture. If the sentence was true, subjects pressed a key on the right; if it was false, they pressed a key on the left. There were four blocks of 80 trials each.

Mental Rotations Task. On each trial, the subject was shown a pair of figures, each figure representing a three-dimensional object composed of ten cubes. (See Figure 1.) The subject's task was to determine whether the two figures represented the same or different objects. The subject pressed the right-hand key if the two pictures depicted the same object and the left-hand key if they represented different objects. If the response was incorrect, a tone was presented for 500 msec through headphones.

"Same" pairs could differ by a rotation in the picture plane around an axis perpendicular to the picture plane, or by an "in depth" rotation around a vertical axis. In "same" pairs, the right-hand picture could be brought into congruence with the left-hand picture by a clockwise rotation in depth or in the picture plane of 20, 60, 100, 140, or 180 degrees. Corresponding to every "same" pair, there was a "different" pair in which the left-hand picture was a mirror image of the right-hand picture after rotating for congruence.

On each of the four days, subjects saw 200 slides (two copies each of 100 unique slides). These 200 slides were arranged in five blocks of 40 slides each such that each block contained 20 "same" slides (two each at angular disparities of 20, 60, 100, 140, and 180 degrees in picture plane and in depth) and 20 "different" slides. The order of slides within a block was constant, but the order of blocks differed on each day for each subject according to a Latin square.

RESULTS

Discussion of the results will be organized in four main sections. In the first section, each experimental task will be discussed separately. Both group results and individual differences analyses will be presented. In the second section, the relationships among experimental tasks will be described. Confirmatory factor analysis was used to test the hypothesis that the data could be fit by a model including a single factor for each of the three experimental tasks. In the third section, analyses of the psychometric tests will be discussed. Here confirmatory factor analysis was used to test the fit of the data to a model incorporating four ability factors, Gc, Gf, Gv, and CPS. In the final section, psychometric and information processing models will be combined in order to determine the relationship between the two types of measures.

Experimental Tasks

Mental Rotations.

Group Results. Day 1 of the computerized mental rotations task was considered practice. Data from Days 2, 3, and 4 were combined to compute each subject's mean RT and percent errors in each condition. Figure 2 displays mean RT across subjects on correct "same" responses as a function of angle and plane of rotation. Percentage of errors in each condition is also shown. RTs on correct "same" trials were subjected to a repeated measures analysis of variance (ANOVA) in which the factors were plane and angle of rotation. The main effects of plane and angle of rotations were significant, $F(1,83)=22.5$, $p<.001$ and $F(4,83)=389$, $p<.001$ respectively, as was the interaction, $F(4,332)=92$, $p<.001$.

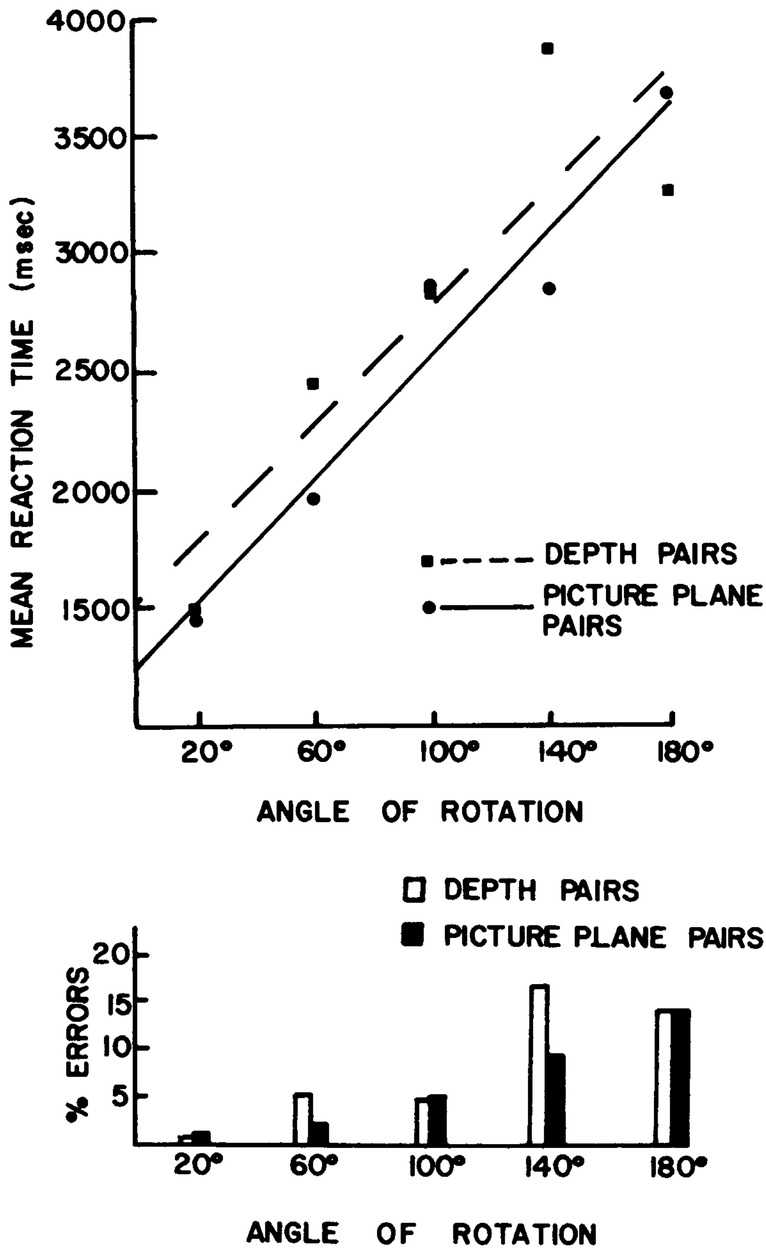


FIG. 2. Reaction time and errors as a function of angle and plane of rotation, mental rotations task, computerized version.

In Shepard and Metzler's data, RT for both picture plane and depth rotations was a linear function of angle of rotation. In our data, RT clearly increased as a function of angle of rotation, but there were obvious deviations from linearity. Separate analyses of "same" trials for picture plane and depth rotations showed that in each case the linear component accounted for a very large proportion of the variation between conditions (r^2=.95 for picture plane and .78 for depth rotations), but the deviations from linearity were also highly significant. These deviations were not the result of the fact that our subject population was more heterogeneous in spatial ability than Shepard and Metzler's, since the same pattern of results occurred when we analyzed data from the very high spatial ability subjects separately. They may have occurred because we used only a subset of the item pairs used by Shepard and Metzler, and inadvertently chose particularly difficult items in certain conditions.

Individual Differences. Data for most individual subjects also displayed a strong linear relationship between RT and angle of rotation. For picture plane rotations, the median value of the correlation between RT and angle of rotation for individual subjects was .94 and the range was .67 to 1.00. For depth rotations, the median was .88 and the range was .59 to .98.

For each subject, the slope and intercept of the function relating "same" RT to angle of rotation was computed. Mean RT and percentage of errors over same and different trials were also computed. These measures were computed separately for picture plane and depth trials. Reliability was estimated by correlating measures based on even and odd trials, and correcting for length using the Spearman-Brown formula. Reliability, mean, standard deviation, and range for each of the eight measures are shown in Table 2.

The correlations between corresponding picture plane and depth measures were .92 for total RT, .81 for percent errors, .71 for slope, and .79 for intercept. These high correlations support Shepard and Metzler's hypothesis that the same process underlies performance on the two types of trials. Since the correlations between picture plane and depth measures were so high, the two types of trials were combined to compute the measures of slope, intercept, mean RT, and percent errors used in the remainder of the analyses.

Paper and Pencil Measures. The paper and pencil version of the mental rotations task was designed to be as similar as possible to the computerized version, but to be amenable to group administration and to require a short amount of time. A typical item is shown in Figure 3a. Subjects were instructed to mark "S" if the two figures represented the same object, and "D" if they were different. Items involved rotations within the picture plane of 30, 60, 90, 120, 150, or 180 degrees. The test was composed of four sections of 24 items each. The first was a practice section including items of all possible angles of rotation. The second through fourth sections were of increasing difficulty, the second involving rota-

TABLE 2
Reliability, Mean, Standard Deviation (*SD*) and Range for Mental Rotation Measures

	Reliability	Mean	*SD*	Range
All Trials				
Mean RT	.99	2911	805	1247–4896
Percent Errors	.95	8.24	5.13	1.17–22.00
Slope	.89	12.98	4.70	3.83–30.92
Intercept	.95	1362	510	605–3192
Picture Plane Trials				
Mean RT	.99	2951	779	1231–4951
Percent Errors	.92	8.35	5.64	1.00–22.67
Slope	.79	13.38	4.88	3.96–28.55
Intercept	.89	1219	502	471–3020
Depth Trials				
Mean RT	.99	2893	874	1264–4986
Percent Errors	.86	8.14	5.12	1.00–24.33
Slope	.82	12.57	5.27	3.69–33.28
Intercept	.91	1506	576	617–3565

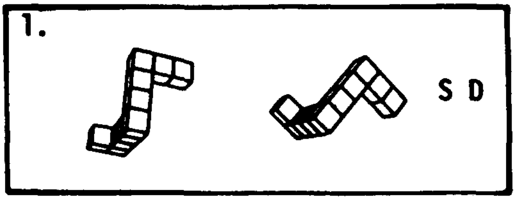
tions of 30 and 60 degrees, the third 90 and 120 degrees, and the fourth 150 and 180 degrees. The time limits for the four sections were 2, 1½, 2, and 2½ minutes respectively. The test was administered twice, once on Day 1 and once on Day 4 of the experiment.

By dividing the time limit for a given section by the number of items completed correctly within that section, a measure of time per correct item was obtained for each subject. This measure corresponds to the RT measure derived from the computerized version of the mental rotations task. Note, however, that "time per correct item" reflects speed on both "same" and "different" items, whereas RTs for these two types of trials can be differentiated in the computerized version. Figure 4 shows mean time per correct item over subjects on Sections 2, 3, and 4 for each administration of the mental rotations test. In spite of the roughness of the measure and the fact that angle of rotation is confounded with order, time per correct item is a quite linear function of angle of rotations within a section.

For each subject, four measures were computed from each administration of the paper and pencil mental rotations test: a) total number correct, b) percent of errors (number of errors divided by number attempted), c) slope of the function relating time per correct item and average angle of rotation within a section, and d) intercept of this function. The mean of scores from the first and second administration were used in all further analyses. Reliabilities of these measures, based on the correlations between Test 1 and Test 2 corrected for length, were .85, .77, .59, and .51 respectively.

One of the purposes of this study was to determine whether measures obtained from a group-administered paper and pencil test would roughly approximate

a. Mental Rotations



b. Letter-Matching

	NI			PI	
1.	Nn	S D	1.	AE	S D
2.	bB	S D	2.	ba	S D
3.	Bn	S D	3.	AA	S D
4.	eE	S D	4.	BN	S D

c. Sentence Verification

1. Plus below star. $\overset{+}{*}$ T F

2. Plus isn't below star. $\overset{*}{+}$ T F

FIG. 3. Sample items from the three paper and pencil tests: a) mental rotations; b) letter-matching; c) sentence verification.

measures derived from much longer and more expensive computerized procedures. Correlations between measures derived from the computerized mental rotations task and from the paper and pencil test are shown in Table 3. The correlation between number correct on the paper and pencil test and overall RT on the computer version is reasonably high (.63), as is the correlation between percent cor-

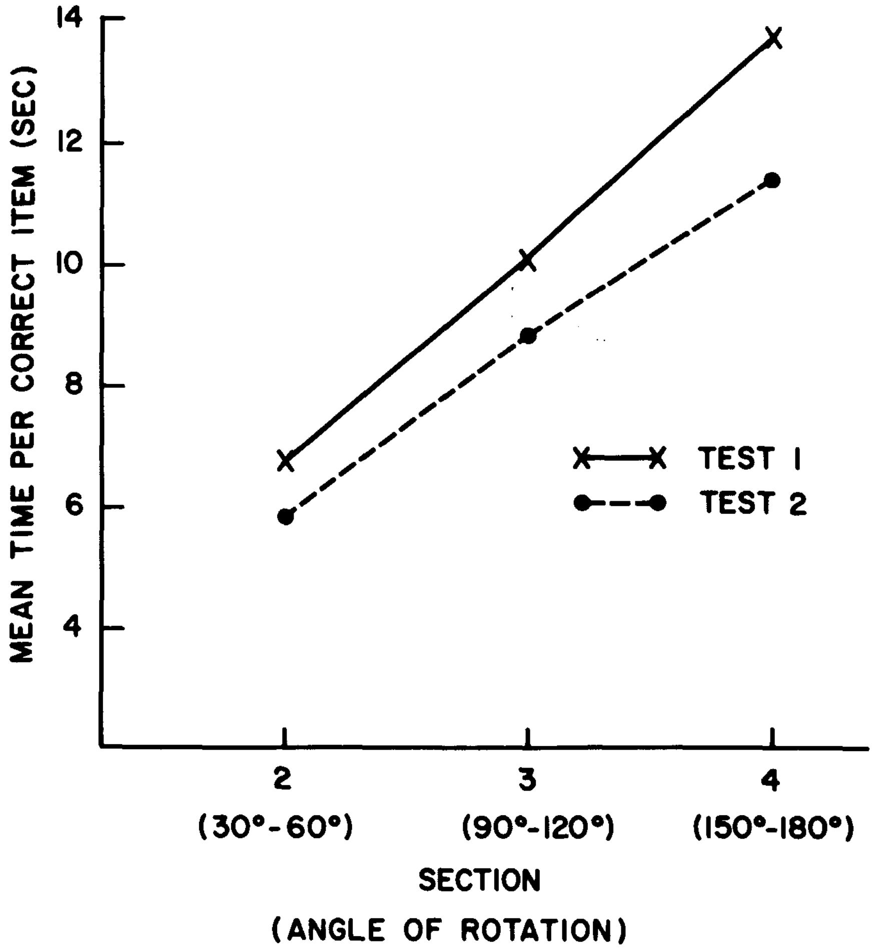


FIG. 4. Time per correct item as a function of section (angle of rotation) in the paper and pencil version of the mental rotations task.

rect in the two versions (.58). The correlations between slopes (.43) and intercepts (.27) are lower. Corrected for attenuation, the correlations between computer and paper and pencil measures are .69, .68, .59, and .39.

Letter-Matching

Computerized Measures. The four conditions in the letter matching task were physical identity (PI, e.g., AA), name identity (NI, e.g., Aa), different-same case, (DSC, e.g., ab), and different-different case (DDC, e.g., Ab). Mean RTs in PI and NI trials were 508 and 604 msec respectively. The 96 msec difference be-

TABLE 3
Correlations Between Computer and Paper and Pencil Measures of Mental Rotations

	Paper and Pencil Measures			
Computer Measures	Total Correct	Percent Errors	Slope	Intercept
Mean RT[a]	−.63**	.43**	.44*	.19*
Percent Errors[a]	−.27**	.58**	.20*	.15
Slope[b]	−.48**	.21*	.43**	.02
Intercept[b]	−.54**	.52**	.32**	.27**

*$p < .05$
**$p < .01$
[a]Based on all trials
[b]Based on same trials only

tween NI and PI is a typical finding in this type of letter matching task: college students take an average of 80 to 100 msec longer to respond that two letters have the same name when they are the same in name only than when they are also physically identical (Posner & Mitchell, 1967; Hunt, Frost & Lunneborg, 1973; Hunt, Lunneborg & Lewis, 1975).

For each subject, six measures were derived from the computerized version of the letter matching task: mean RT on PI, NI, DSC, and DDC trials, the NI-PI difference, and percent errors on all trials combined. Reliability, mean, standard deviation, and range for each of these measures is shown in Table 4.

Paper and Pencil Measures. Typical items from the letter matching test are shown in Figure 3b. Subjects were instructed to mark "S" if the two letters were the same and "D" if they were different. In each section, there were 120 items

TABLE 4
Reliability, Mean, Standard Deviation (*SD*) and Range for Letter-Matching Measures

	Reliability	Mean	*SD*	Range
Computer Measures				
PI RT	.98	508	53	409–745
NI RT	.98	604	72	481–923
DSC RT	.97	590	60	490–790
DDC RT	.97	632	68	520–863
NI–PI	.83	96	33	35–206
Percent Errors	.75	4.4	2.1	0.8–11.2
Paper and Pencil Measures				
Total Correct	.92	338	52	201–433
Time/Correct Item, PI & DSC	.94	810	136	625–1304
Time/Correct Item, NI & DDC	.92	1048	191	755–1759
NI–PI	.68	238	95	26–530
Percent Errors	.42	.8	.8	0–3.5

and the time limit was 1¼ minutes. Section 1 included both physically identical and name identical items and was used for practice. In Sections 2 and 4, all "same" items were physically identical and all different items were in the same case; in Sections 3 and 5, all same items were identical in name only and all different items were in different cases. By dividing the 1¼-minute time limit by the number of items completed correctly within a section, a measure of time per correct item was obtained. Table 4 allows a comparison of time per correct item on the paper and pencil test to RT on the computer version. (Note, however, that time per correct item on Sections 2 and 4 reflects both PI and DSC RTs, and time per correct item on Sections 3 and 5 reflects both NI and DDC RTs.) Average time per item was much longer on the paper and pencil than the computerized version, and the NI-PI difference was more than twice as great.

For each subject, five measures were computed from the paper and pencil test: a) total number correct on Sections 2 through 5; b) time per correct item on Sections 2 and 4 (PI and DSC); c) time per correct item on Sections 3 and 5 (NI and DDC); d) difference between c and b, which roughly corresponds to the NI-PI difference; and e) percent errors on Sections 2 through 5. Reliability, mean, standard deviation, and range for each of these measures is shown in Table 4. Reliabilities are based on the correlations between scores from Sections 2 and 3 and scores from Sections 4 and 5, corrected for length.

Table 5 shows correlations between scores on the computerized and paper and pencil measures of letter matching. Correlations between speed measures (RT and time per correct item) are moderately high, ranging from .49 to .57 for corresponding measures. However, the correlation between the two NI-PI measures is only .29 (.39 when corrected for attenuation), indicating that these two measures could not be used interchangeably. Factors related to format seem to be important in determining the NI-PI score. One of these factors may be the fact that PI and NI trials were mixed in the computer version of the task and blocked in the paper and pencil version.

TABLE 5
Correlations Between Computer and Paper and Pencil Measures of Letter-Matching

	Paper and Pencil Measures				
Computer Measures	Total Correct	PI & DSC	NI & DDC	NI–PI	Percent Errors
PI RT	−.56**	.57**	.54**	.26**	.07
NI RT	−.53**	.51**	.53**	.33**	.10
DSC RT	−.53**	.49**	.53**	.36**	.06
DDC RT	−.48**	.42**	.50**	.40**	.08
NI–PI	−.25*	.20*	.29**	.29**	.11
Percent Errors	−.23*	.19*	.22*	.18*	.23*

*$p < .05$
**$p < .01$

Sentence Verification

Group Results. Mean correct RT was computed in each of the eight conditions formed by the factorial combination of above and below, true and false, and affirmative and negative. In Figure 5, these observed values are compared to the values predicted by the Clark and Chase and Carpenter and Just models. Predicted values were estimated in each case by the least squares method. Each of the two models accounted for 97% of the variation betwen the means of the various conditions. In the case of the Clark and Chase model, four parameters were used to account for the variation betwen eight conditions, and in the case of the Carpenter and Just model, two parameters were used to account for the variations between four conditions. ("Above" and "Below" RTs were averaged together.) The fact that each model accounts for 97% of the variation between conditions is less impressive in light of the fact that 92% of the variation between the eight conditions handled by the Clark and Chase model and 94 % of the variation between the four conditions handled by the Carpenter and Just model is accounted for by the negation effect alone. The greatest deviation from the predictions of both models was the finding that RT to true negative sentences was almost identical to RT to false negative sentences, whereas both models predict that true negatives should take longer.

Variation between conditions was analyzed using a repeated measures ANOVA in which the three factors corresponded to three process parameters of the Clark and Chase model: a) negatively or affirmatively stated sentence; b) match or mismatch between embedded strings (e.g., the contrast between sentences which did and did not involve the falsification parameter); and c) above or below as the relational term. The main effect corresponding to each of these parameters was highly significant: for the negation effect $F(1,71) = 602, p < .001$; for the falsification effect $F(1,71) = 53$, $p < .001$; for the markedness effect $F(1,71) = 68, p < .001$. However, two interactions were also significant: negation by falsification $F(1,71) = 53$, $p < .001$ and negation by markedness, $F(1,71) = 30$, $p < .001$. The negation by falsification interaction reflects the fact that there was a strong falsification effect for affirmatively stated sentences (FA − TA = 268), while there was no falsification effect for negatively stated sentences (TN − FN = 5). Similarly, the negation by markedness interaction reflects the fact that the markedness effect was greater for affirmative sentences (below RT − above RT = 186) than for negative sentences (below RT − above RT = 55).

The interaction between negation and falsification is counter to specific predictions of both the Clark and Chase and the Carpenter and Just models. Both models state that the negation and falsification effects should additive. However, the finding of an interaction between negation and falsification is quite common (Clark & Chase, 1972, Experiment 2; MacLeod, Hunt & Mathews, 1978; Lansman, 1977),

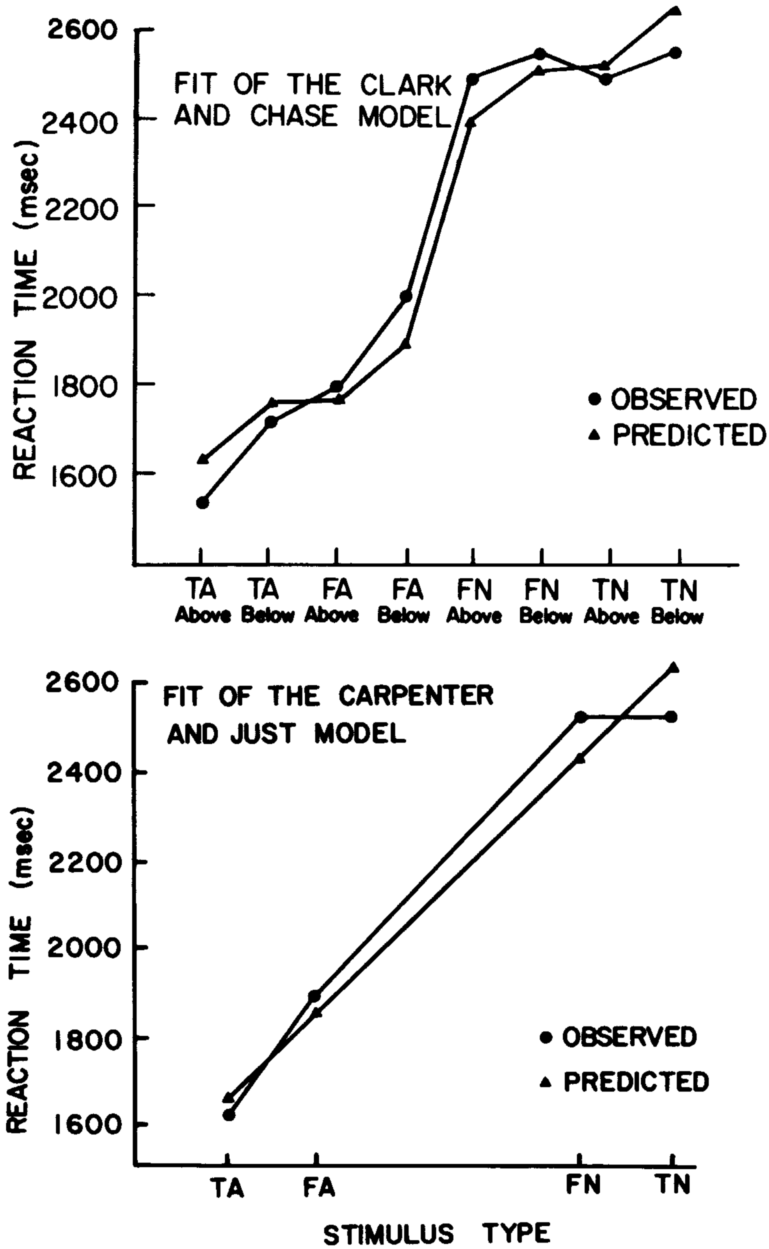


FIG. 5. Fits of the Clark and Chase and Carpenter and Just models to the sentence verification reaction times.

and there are at least two explanations for it. Both Clark and Chase and Carpenter and Just discuss the possibility that subjects "recode" negative sentences into corresponding affirmative sentences (e.g., translate "Plus is not above star" into either "Star is above plus" or "Plus is below star"). Such recoding strategies would produce longer RTs for FN than for TN sentences. A second strategy that yields this result is the "spatial strategy" discussed by MacLeod et al. (1978; Mathews, Hunt & MacLeod, 1980), in which subjects transform each sentence into the corresponding visual image and then compare the image to the picture.

The overall error rate in the sentence verification task was 6.1%, which is quite low for this type of task. In general, higher error rates were associated with longer reaction times, except that subjects made more errors on true negative than false negative sentence-picture pairs.

Individual Differences. Each subject's data were analyzed to determine how well they were fit by both the Clark and Chase and the Carpenter and Just models. Median r^2 for the Clark and Chase model was .93 with a range of .57 to .99. Median r^2 for the Carpenter and Just model was .94 with a range of .54 to 1.0. However, just as in the case of the group data, these figures are somewhat misleading since the negation effect alone accounts for such a large proportion of the variation between conditions.

According to the Clark and Chase model of sentence verification, the two possible measures of the negation parameter (FN - TA and TN - FA) should be highly correlated with one another. By the same reasoning, the two measures of the falsification parameter (FA - TA and TN - FN) should be correlated. The Carpenter and Just model makes the additional prediction that estimates of the negation parameter should be highly correlated with estimates of the falsification parameter, since the same process is responsible for both. Table 6 shows correlations among the various parameter estimates. Since correlations between two difference scores containing the same component (e.g., between TN - FA and FA - TA) are mathe-

TABLE 6
Correlations Between Negation and Falsification Parameters of the Sentence Verification Task

	Odd Trials			
Even Trials	Negation I	Negation II	Falsification I	Falsification II
Negation I (FN–TA)	.87**	.51**	.44**	−.13
Negation II (TN–FA)		.82**	.06	.51**
Falsification I (FA–TA)			.71**	−.05
Falsification II (TN–FN)				.69**

$^{**}P < .01$

TABLE 7
Reliability, Mean, Standard Deviation, (*SD*) and Range for Sentence Verification Measures

	Reliability	Mean	*SD*	Range
Computer Measures				
Affirmative RT	.99	1763	405	1106–3060
Negative RT	.99	2534	576	1442–4079
Negation Time	.94	771	267	318–1646
Percent Errors	.75	6.1	2.9	0–14.8
Paper and Pencil Measures				
Total Correct	.94	186	35	101–252
Time/Affirmative Item	.56	2766	512	2012–4868
Time/Negative Item	.75	4078	1109	2343–7495
Negation Time	.48	1312	926	−183–4636
Percent Errors	.69	3.6	2.9	0–16.4

matically dependent, measures listed across the top are based on odd trials and measures listed down the side are based on even trials. Thus the correlations in the diagonal provide estimates of the reliabilities of the difference scores.

The correlation between the two estimates of the negation parameter is reasonably high, .51, supporting the notion that the same process may underlie these two measures. However, the correlation between the two estimates of the falsification parameter is near zero, -.05, clearly disconfirming the hypothesis that the same process underlies these two parameters. In a sense then, the analysis of individual differences underscores conclusions based on the analysis of group means. The negation effect is strong and accounts for a large proportion of the variation between means. It can be reliably estimated by either of two difference scores (FN - TA and TN - FA), and these two difference scores are correlated. The falsification effect is much weaker, and interacts with the negation effect in a way not predicted by either of the principal models of sentence verification. Since the two estimates of the falsification parameter, though reliable, are uncorrelated, they cannot be argued to be measures of the duration of the same process. For this reason, the falsification parameter was dropped from further analysis. A combined measure of negation time (mean on all negative trials minus mean on all affirmative trials) was used in relating computer to paper and pencil measures.

Table 7 shows the reliability, mean, standard deviation, and range for each of the measures used in further analyses. Percent errors in all conditions combined is also shown. As in the case of the mental rotations data, reliabilities were based on the correlations between even and odd trials.

Paper and Pencil Measures. Some typical items from the sentence verification test are shown in Figure 3c. Subjects were instructed to mark "T" if the sentence was a true description of the picture and "F" if it was not. The test contained five sections of 64 items each. The time limit for each section was 2½ minutes. The first section was used for practice, and contained 50% affirmative and 50%

negative sentences. Sections 2 and 4 contained 75% affirmative and 25% negative sentences, while Sections 3 and 5 contained 25% affirmative and 75% negative sentences. Weighted combinations of the number of items correctly completed in Sections 2 and 3 (and in Sections 4 and 5), yielded estimates of the time per correct negative and affirmative item. Table 7 allows a comparison of time per correct affirmative and negative item in computer and paper and pencil versions of the task. In the paper and pencil as well as the computer version, negatively stated sentences took considerably longer to verify than affirmative sentences.

For each subject, five measures were computed: a) total number of items answered correctly, b) time per correct affirmative item, c) time per correct negative item, d) negation time (time per correct negative item minus time per correct affirmative item), and e) percent of errors (number of errors divided by the number of items attempted). Reliability, mean, standard deviation, and range for each score are shown in Table 7. Reliabilities are based on the correlations between scores based on Sections 2 and 3 and scores based on Sections 4 and 5 corrected for length.

Table 8 shows the correlations between computer and paper and pencil versions of the sentence verification task. Correlations between the total number correct on the paper and pencil test and the two RT measures on the computer version are quite high (−.75 and −.72), as are correlations between corresponding RT measures (.63 for the two affirmative RT measures and .70 for the two negative RT measures). Thus the paper and pencil measure could be used as a measure of performance in the sentence verification task in situations where computerized procedures were unfeasible. The correlation between the two negation time measures is lower, .40 (.60 when corrected for attenuation).

Measurement of Unobserved Factors

The previous section described within-task analyses of the information processing measures. In this section, multivariate analyses of information processing and psychometric measures are described. As a first step, the relationships among measures within each of the two domains were examined. Factors were defined that summarized performance on both the information processing tasks and the

TABLE 8
Correlations Between Computer and Paper and Pencil Measures of Sentence Verification

	Paper and Pencil Measures				
Computer Measures	Total Correct	Affirmative RT	Negative RT	Negation Time	Percent Errors
Affirmative RT	−.75**	.63**	.72**	.52**	.34**
Negative RT	−.72**	.54**	.70**	.55**	.39**
Negation Time	−.41**	.22*	.43**	.40**	.32**
Percent Errors	−.28**	.27*	.33**	.25**	.36**

*$p < .05$
**$p < .01$

psychometric tests. These two sets of ability factors were then related in a single analysis.

Maximum likelihood methods of confirmatory factor analysis as embodied in the LISREL IV program of Joreskog and Sorbom (1978) were used throughout. In this method of analysis, one restricts the allowable forms of a factor analytic solution, and then obtains the likeliest solution that satisfies the specified restrictions. The restrictions are made explicit by specifying the values of a sufficient number of parameters in the matrices that express the common factor analysis model:

where

y is the vector of observed variables
Λ is the pattern matrix of coefficients
η is the vector of unobserved factors
ϵ is the vector of unobserved residuals
Ψ is the factor covariance matrix
θ is the residual covariance matrix

An appropriate specification of elements of the Ψ, η, and θ matrices identifies a unique solution. These specifications determine the number of factors, which variables load on which factors, which factors are correlated, and the pattern of residual correlations. The unspecified remaining parameters are estimated by LISREL, which also supplies a χ^2 goodness of fit statistic for the specified model.

The complete correlation matrix, upon which all confirmatory factor analyses are based, is presented in Appendix A.

Relationship among information processing measures. Our goal was to define one set of general factors that would describe performance on both computer and paper-and-pencil measures. Within each experimental task, the correlations between RT measures based on the computerized version and number correct on the paper and pencil version were quite high. However, the correlations between corresponding derived measures (i.e., slope of the RT function for the mental rotations tasks, the NI-PI difference in the letter matching tasks, and negation time for the sentence verificaion task) were low. For this reason, we did not use these derived measures in defining the general factors. Examination of the first order correlations between psychometric and information processing measures indicated that little information was lost by omitting the derived scores, since correlations involving derived measures showed the same pattern as correlations involving mean RT and error scores. The only exception to this generalization involved the NI-PI difference score, which was more highly correlated with the Gc measures than either the PI or the NI measure alone. The NI-PI measure will be discussed separately below.

The model for the experimental tasks stipulated one factor for each of the three tasks. Both computerized and paper and pencil measures were used to define these three factors. Performance on the paper and pencil tests was represented by num-

TABLE 9
Three Common Factor Analysis Models for Information Processing Tasks Λ Factor Pattern Matrix*

Variable		Factor									Uniqueness		
		Mental Rotation			*Letter Matching*			*Sentence Verification*					
		Model			*Model*			*Model*			*Model*		
		Ia	*Ib*	*Ic*	*Ia*	*Ib*	*Ic*	*Ia*	*Ib*	*Ic*	*Ia*	*Ib*	*Ic*
	Depth RT	73	77	75							46	44	44
	Picture Plane RT	76	79[a]	83[f]							42	40	40
Mental	P&P Section 1	86	79[a]	83[f]							26	33	27
Rotations	P&P Section 2	81	79[a]	83[f]							35	46	35
	P&P Section 3	88	79[a]	83[f]							23	44	24
	P&P Section 4	83	79[a]	83[f]							31	47	33
	NI RT				93	70[b]	87[g]				13	48	15
	PI RT				93	71[c]	86[h]				15	47	17
Letter	DSC RT				94	65	94				12	56	11
Matching	DDC RT				93	61	93				13	61	13
	P&P NI				56	70[b]	87[g]				69	52	77
	P&P PI				59	71[c]	86[h]				66	50	70
	True Aff. RT							96	87[d]	95[i]	08	23	08
	False Aff. RT							98	87[d]	95[i]	05	26	05
Sentence	True Neg. RT							90	83[e]	90[j]	20	39	20
Verification	False Neg. RT							94	83[e]	90[j]	13	31	13
	P&P Aff.							77	87[d]	95[i]	41	26	43
	P&P Neg.							77	83[e]	90[j]	42	32	42

ψ Factor Correlation Matrix

	Mental Rotation			Letter Matching			Sentence Verification		
	Ia	Ib	Ic	Ia	Ib	Ic	Ia	Ib	Ic
Mental Rotations	1.00	1.00	1.00						
Letter Matching	.07	.14	.08	1.00	1.00	1.00			
Sentence Verification	.11	.14	.18	.59	.77	.59	1.00	1.00	1.00

Goodness of Fit

	Residual Correlation Allowed?	χ^2	*df*	*p*
Model Ia	No	598.4	132	.0000
Model Ib	Yes	108.2	69	.0018
Model Ic	No	637.5	142	.0000

*Blanks denote fixed zeros. The superscripts a-j mark parameters constrained to be equal. Decimal points have been suppressed.

ber of items answered correctly on the various sections of the tests. Performance on the computerized tests was measured by RT in the various conditions. The specific measures used in the analysis are shown in Table 9.

In defining our three information processing factors, we wanted to omit variance specific to one or the other testing format. In some designs, method-specific variance can be removed from task-specific general factors by defining one method factor for each format, but such a model requires three methods to be identified (Kenny, 1979). Since this study involves only two method domains, this type of analysis is impossible. An alternative method of removing method-specific variance is to allow the residuals associated with all measures based on a single testing method to be inter-correlated. These correlated errors reflect all influences, including method and excluding task, that account for correlations between variables. When such correlated errors are estimated, factor loadings are purged of method effects and all other effects common to pairs of tests within the same format. Three models were considered: Model 1a with uncorrelated residuals; Model 1b in which the residuals of same-format tests were allowed to be correlated and certain parameters were constrained to achieve identification; and Model 1c, in which the identifying constraints of Model 1b, but not the assumption of correlated errors, were imposed on Model 1a. In all three models, each measure was allowed to load on a single factor, and the three factors were allowed to be correlated, as in a traditional oblique simple structure solution. The reported results, shown in Table 9, are for standardized variables and factors.

In Model 1a, the loading of each task on its corresponding task factor was free to vary, all other factor loadings were fixed at zero, and the residual variances were uncorrelated. The fit of the model was poor, as indicated by the highly significant χ^2. In Model 1b, the residuals of same-format measures were allowed to be correlated. In order to identify a solution with correlated residuals, the loadings of analogous computer and paper and pencil measures were constrained to be equal. Although these constraining assumptions are not trivial, neither are they reckless. Each constraint matches tests designed explicitly to measure the same factor with two different methods. Allowing residuals of same-format measures to be correlated significantly improved the fit of the model to the data. (Difference in $\chi^2 = 490$, $df = 63$, $p < .001$). The correlations between residuals were highest for within-task, within-method variables (some were as high as .4 or .5), but there were also noteworthy cross-task, within-method residual correlations. Residual correlations among paper and pencil measures tended to be lower than residual correlations among computerized measures.

It is not really possible to test the identifying constraints of Model 1b (by definition, since the same model without them would not be identified). It is possible, however, to compare the fit of Model 1a to Model 1c, which incorporates the equality constraints of Model 1b, but does not allow correlated errors. Although the difference in χ^2 between Models 1a and 1c cannot be regarded as a statistical test of the constraining assumptions in Model 1b (because 1b also has correlated errors), a large difference in χ^2 would cast doubt on the plausibility of the assumptions. There is a significant decrease in 1c relative to 1a, but it is small in magnitude compared to the noteworthy difference in fit between Models 1a and 1b. Though the χ^2 for Model 1b was still significant, indicating some lack of fit, this model was accepted as a satisfactory description of the relationships among the information processing measures. No further changes were thought to be theoretically defensible.

An interesting result of this analysis appers in the matrix of correlations among the three factors. Although the estimated correlation between the two verbal processing factors was quite high ($r = .77$), neither of these factors was highly correlated with the mental rotations factor ($r = .14$ in each case). This pattern of relationships underscores the distinction between verbal and spatial abilities in this college population. The independence of verbal and spatial measures is also indicated by the first order correlations. Shown in Table 10 are the correlations between overall performance measures in the mental rotations tasks and overall performance measures from the letter matching and sentence verification tasks. None of these correlations exceeds .26, and none of the cross-task, cross-format correlations is significantly different from zero. When measures differed in both content and format, the correlations between them were near zero.

Relationships Among Psychometric Measures. The psychometric tests used in this study were selected according to fairly explicit measurement hypotheses, which are represented in Table 11. An attempt was made to overdetermine four

TABLE 10
Correlations Between Mental Rotations and Letter–Matching and Sentence Verification Measures

	Mental Rotations	
	RT Over All Conditions (Computer Version)	Number Correct, All Sections (Paper and Pencil Version)
Sentence Verification, RT Over All Conditions (Computer Version)	.25*	−.04
Letter–Matching, RT Over All Conditions (Computer Version)	.13	.07
Sentence Verification, Number Correct Over All Sections (Paper and Pencil Version)	−.12	.19*
Letter–Matching, Number Correct Over All Sections (Paper and Pencil Version)	−.11	.26*

*$p < .05$

simple structure factors by including Matrices, Letter Series, and Common Analogies as indicants of Gf; Vocabulary, Remote Associations, General Information, and Esoteric Analogies as measures of Gc; Card Rotations, Figures, Cubes, Form Board, Surface Development, and Paper Folding as exemplars of Gv; and Identical Pictures, Finding A's, and Canceling Numbers as markers for CPS. Table 11 shows the number of items and reliability for each of these tests.

Model 2a, stated and estimated in Table 12, incorporates the measurement hypotheses of Table 11. Each measure was allowed to load on only one factor (Gf, Gc, Gv, or CPS), and the factors were allowed to be intercorrelated. The fit is reasonably good, although χ^2 is significant at conventional alpha levels. Model 2b involves several relaxations of Model 2a. Three of the Gv measures, Card Rotations, Figures, and Cubes, which are simpler than the others and therefore involve more of a speed factor, were allowed to load on CPS as well as Gv. Remote Associations was also allowed to load on CPS, since there was wide variation in the number of items completed on this test. Finally, the Finding A's test was allowed to load on Gf, since printing of this test was poor and the test required something similar to a Gestalt completion ability, which is known to correlate with Gf.

The parameter estimates for Model 2b, shown in Table 12, provide a good fit to the data. Deviations from this model were insignificant by conventional statistical criteria. The correlations among the four factors were quite low.

Of the four factors, Gf was the most poorly defined. The loadings of two of the three tests chosen to measure Gf were quite low, probably because these tests were relatively unreliable. As a result, the Letter Series test assumed overriding importance in determining the Gf factor.

TABLE 11
Measurement Hypothesis and Reliabilities for Psychometric Variables

Variable	Hypothesis	# Items	Reliability
Matrices	Gf	5	.57[a]
Letter Series	Gf	23	.90[a]
Common Analogies	Gf	12	.51[a]
Vocabulary	Gc	18	.62[a]
Remote Associations	Gc	19	.71[a]
Esoteric Analogies	Gc	17	.65[a]
General Information	Gc	21	.65[a]
Card Rotations	Gv	20	.84[b]
Cubes	Gv	42	.84[b]
Figures	Gv	20	.87[b]
Paper Folding	Gv	20	.86[a]
Surface Development	Gv	60	.93[a]
Form Board	Gv	20	.78[a]
Identical Pictures	CPS	48	.92[b]
Finding A's	CPS	40	.86[b]
Cancelling Numbers	CPS	50	.87[b]

[a]$KR20r_{xx}$
[b]Split-half

TABLE 12
Two Common Factor Analysis Models for Ability Measures
Λ Factor Pattern Matrix*

Variable	Factor: *Gc* Model 2a	*Gc* Model 2b	*Gf* Model 2a	*Gf* Model 2b	*Gv* Model 2a	*Gv* Model 2b	*CPS* Model 2a	*CPS* Model 2b	Uniqueness Model 2a	Uniqueness Model 2b
Esoteric Analogies	85	84							28	30
Vocabulary	71	73							50	47
General Information	62	61							62	62
Remote Associations	34	35						24	88	83
Common Analogies		23	29	22					92	88
Matrices			43	35					81	88
Letter Series			64	79					59	38
Figures					79	67		53	38	31
Cubes					73	68		29	46	47
Card Rotations					82	73		38	32	35
Paper Folding					43	54			82	71
Surface Development					69	79			53	38
Form Board					62	62			62	62
Identical Pictures							54	52	71	74
Finding A's				43			68	62	54	51
Cancelling Numbers							42	49	82	76

ψ Factor Correlation Matrix

	Gc Model 2a	Gc Model 2b	Gf Model 2a	Gf Model 2b	Gv Model 2a	Gv Model 2b	CPS Model 2a	CPS Model 2b
Gc	1.00	1.00						
Gf	.30	.20	1.00	1.00				
Gv	.18	.19	.14	.10	1.00	1.00		
CPS	.11	−.03	.28	−.14	.36	−.04	1.00	1.00

Goodness of Fit

	χ^2	*df*	*p*
Model 2a	139	98	.0039
Model 2b	104	92	.1775

*Blanks denote fixed zeros. Decimal points have been suppressed.

Relationship Between Information Processing and Psychometric Factors. The purpose of this analysis was to estimate the correlations between the three information processing factors of Model 1b and the four ability factors of Model 2b. This was accomplished in LISREL by specifying a seven-factor Model 3 in which the 12 correlations between the two sets of factors were free, and in which all other parameters were fixed at Model 1b and Model 2b values. This procedure, which necessarily caused some lack of fit relative to less stringent models, ensured that the factors had identical meanings in all analyses. Ability variables were not allowed to influence the factor structure of the information-processing tasks, and vice versa. There was thus no ambiguity in interpreting the within-domain oblique factor structure, and the between-domain factor correlations.

TABLE 13
Correlations Between Information Processing Factors of Model 1b and Ability Factors of Model 2b

	Mental Rotations	Letter Matching	Sentence Verification
Gc	.04	.07	.28
Gf	−.10	.02	.00
Gv	.78	−.10	−.07
CPS	.21	.69	.38

These correlations estimate the linear relationship between experimental factors, from which the effects of format have been removed, and ability factors, which could not be separated from the effects of their paper and pencil format. It was not possible to remove format effects from the ability variables because the design nests them within the paper and pencil format. A more ambitious design crossing abilities with formats would have permitted the estimation of between-domain factor correlations purged of method effects for both factors, analogous to a partial correlation; the correlations estimated in the present design are analogous to part correlations.[3]

The estimated factor correlations of Model 3 are presented in Table 13. The mental rotations factor was strongly correlated with the Gv factor and weakly correlated with the CPS factor. This pattern is reasonable since mental rotations involves spatial reasoning and Gv is a spatial reasoning factor. The letter matching factor was highly correlated with CPS and uncorrelated with the other factors. This again is not surprising, since letter matching is a highly speeded, clerical type task. Finally the sentence verification factor was correlated with both CPS and Gc factors.

In previous studies, Hunt and several other investigators have found a relationship between the NI-PI differences score and verbal ability. The present study indicates that speed on the letter-matching task, when results are summed over NI and PI conditions, is highly correlated with the CPS factor. Individual variation in the processes common to the two conditions is related to the fairly low level clerical skills measured by the CPS tests. However, further analyses revealed that the variance specific to NI was also related to the Gc factor. The details of this analysis are reported in a separate paper (Donaldson, 1980). Donaldson used maximum likelihood techniques to define a factor corresponding to the NI-PI difference. This factor measured variability unique to the NI measure, excluding variability shared by NI and PI measures. The correlation between the "NI-PI" factor and the Gc factor was -.35. This value is very close to the value obtained in previous studies for the correlation between the NI-PI difference score and verbal ability.

[3]A model was also estimated in which the information processing variables were also uncontrolled for format (i.e., Model 1a and 2b were combined). The only noteworthy changes in Table 13 were to depress the correlations of CPS with LM and SV to .52 and .24, respectively.

Thus, although the correlation between NI RT and PI RT was very high (.91), and the factor representing letter-matching speed was correlated with CPS and not Gc, a more detailed analysis indicated that the variability specific to the NI condition was significantly related to the Gc factor.

GENERAL DISCUSSION

In this study, we related theory-based measures of information processing to four explicitly defined mental abilities. Previous research had shown that the information processing measures were related to psychometric test scores. We attempted to locate the measures in a space defined by the Horn-Cattell theory of fluid and crystallized intelligence.

Perhaps the most notable outcome of the study was the high degree of differentiation among intellectual abilities in this college population. This differentiation was evident in all phases of the correlational analyses. First, the four psychometric factors, Gc, Gf, Gv, and CPS were virtually uncorrelated. With the possible exception of Gf, the four factors were quite well defined (i.e., good simple structure and adequate reliabilities). Most of the psychometric measures loaded quite highly on the factor they were chosen to represent. However, none of the correlations between the factors exceeded .2 (the correlation between Gc and Gf). This finding may be contrasted to results reported by Horn and his associates, who often have found correlations as large as .5 between Gc and Gf in samples drawn from more heterogeneous populations (e.g., Horn, Donaldson, & Engstrom, 1981). Our results are consistent with the suggestion (Humphreys, 1981) that a general ability factor accounts for a larger proportion of the variance in a broad, heterogeneous sample than in homogeneous, high-ability populations, such as college students, where group factors are more highly differentiated.

The correlations between the information processing factors underscored the distinction between verbal and spatial processes. The two verbal factors, letter matching and sentence verification, were highly correlated (.77), but neither was correlated with the spatial factor, mental rotations. Even the first-order correlations between verbal and spatial processing measures of the same format were quite low. On the other hand, correlations between letter-matching and sentence verification were extremely high, in spite of the fact that the sentence verification task requires more complex processing skills than the letter-matching task. In terms of individual differences, the content dimension (verbal versus spatial) was more salient than the complexity dimension (letter-matching versus sentence verification).

Finally, and most importantly, the correlations between the information processing and psychometric measures were quite specific. The mental rotations factor was strongly correlated with the Gv factor. The letter-matching factor was strongly related to the CPS factor. The sentence verification factor was moderately correlated with the CPS and Gc factors. If the study were repeated with subjects sampled from a broader ability range, we would probably find the influence of a general ability factor to be greater, causing the specific ability factors to be less differentiated. However, the college population is of considerable interest in itself.

How do these results fit in with previous investigations of information processing and mental abilities? First consider the relationship between mental rotations and Gv. Our results are consistent with those reported by Tapley and Bryden (1977) and Snyder (1972) in suggesting that the speed of rotating a mental image is highly related to psychometrically defined spatial ability. However, our results extend the previous findings by showing that the relationship is specific to spatial ability and does not extend to Gc, Gf, or CPS. The independence of the mental rotations factors from Gc, Gf, and CPS supports the assertion that different cognitive processes are used to solve spatial and verbal reasoning problems. It should be noted, however, that neither this nor previous research supports the conclusion that all tasks which involve pictorial or non-verbal representations draw on Gv or spatial ability. Some of the subjects who participated in our study went on to do a further series of spatial tasks (Glascock, 1979). These tasks were designed to measure the speed of encoding a spatial pattern and the duration of the visual representation of such a pattern. Glascock found these measures to be unrelated to the Gv factor. It seems that in order for task performance to be related to spatial ability, the task must require the subjects to manipulate a visual image, not only to encode and remember it. The Gv factor, as observed by Horn and Donaldson (1980), is thought to involve reasoning and manipulation as well as the formation of visual images.

The analyses reported here, and the subsidiary analysis by Donaldson (1980) amplify previous studies relating letter-matching tasks to verbal ability. Previous studies indicated that the NI-PI difference, which purportedly measures speed of access to verbal codes in long term memory, was correlated with verbal ability, as broadly defined by college entrance examinations. The psychometric tests used in this study allowed us to distinguish between higher level verbal skills, as measured by the Gc factor, and low level clerical skills, as measured by CPS. The variance common to NI and PI was found to be correlated with CPS. Donaldson's analysis also revealed that the variance unique to NI was correlated with Gc. Failure to find a correlation between letter-matching speed and Gf casts doubt on Hogaboam and Pellegrino's (1978) speculation that the letter-matching task draws on an ability to use overlearned symbols in an unusual way.

Other recent findings support the conclusion that verbal ability is related to speed of access to long-term memory. Hunt, Davidson, and Lansman (1981) measured RT to make several types of semantic decisions. For example, subjects were asked to respond as to whether two items belonged to the same category (e.g., robin, sparrow) or to decide whether an item belonged to a certain category (e.g., bird, robin). They found that time to make these semantic decisions was related to verbal ability. Thus the relationship between verbal ability and speed of access to semantic memory is by no means specific to the Posner letter-matching task, as has been argued by Hogaboam and Pellegrino (1978).

Given that there is a relationship between Gc, or verbal ability, and speed of access to well-learned verbal codes, one may ask about the source of this relationship. Do people with fast access to verbal codes find it easier to learn complex verbal skills, such as reading? Or do people with well-developed verbal skills spend more time dealing with words and thereby develop faster access to verbal codes? A recent set of experiments by Jackson (1980) suggests that the former hypothesis is more likely to be true. Jackson taught subjects associations between unfamiliar forms and nonsense syllable "names." Each syllable was associated with two forms. He then asked these subjects to make same-different judgments on the basis of the names of the forms. He found that even in this situation, where high and low ability subjects were equally familiar with form-name associations, fast RTs on the same-different judgments were related to reading skill.

The relationship between verbal ability and speed of access to verbal codes appears to be a well-established finding. However, the correlations are not high. In our study the correlation between the NI-PI factor and verbal ability was $-.35$, which is representative of other findings. Neither the present research nor any other study of its kind has come close to "explaining" the variability in verbal ability scores. This failure is not surprising; verbal ability and Gc are broad traits. Individual differences in these traits are surely related to cognitive processes that can be studied in the laboratory, but are also determined by environmental opportunity, education, and acculturation. It is important to ask how cognitive processes affect the development and maintenance of abilities, but it is naive to expect individual differences in broad aspects of intelligence to be "accounted for" by information processing rates, let alone by any single rate measure.

The fact that there was no correlation between Gf and the information processing measures is of some interest. Fluid intelligence is often described, somewhat loosely, as the ability to solve novel problems. One might expect, then, to find a positive relationship between Gf and performance on laboratory tasks, which certainly involve adjustment to a novel situation. In fact, a careful look at the tests commonly used to measure Gf suggests that they measure a somewhat more specific ability: the ability to discover and apply rules used to generate various kinds of patterns, i.e., inductive reasoning. So far, it has proved difficult to discover the primitive cognitive processes that underlie inductive reasoning ability. Sternberg has suggested that so-called "metacomponents" are important in explaining individual differences in inductive reasoning (Sternberg & Gardner, in press). The term metacomponents refers to the more global strategies and procedures that determine problem-solving success. In explaining inductive reasoning ability, variation in these metacomponents may outweigh variation in the simpler cognitive processes considered here.

The analyses presented here emphasize the close correspondence between the Gc-Gv and verbal-spatial processing distinctions made in both psychometric and experimental psychology. The experimental results complement the psychometric studies by connecting them to a literature that explicates the details of the processes of memory referencing and visual image manipulations.

APPENDIX A
The Complete Correlation Matrix Used for Confirmatory Factor Analyses

	1.	2.	3.	4.	5.	6.
Mental Rotations						
1. Depth RT	1.00					
2. Picture Plane RT	.92	1.00				
3. P&P Sec. 1	.59	.64	1.00			
4. P&P Sec. 2	.56	.57	.70	1.00		
5. P&P Sec. 3	.58	.59	.76	.76	.100	
6. P&P Sec. 4	.54	.59	.75	.63	.78	1.00
Letter Matching						
7. NI RT	.00	.05	−.00	.08	−.01	.05
8. PI RT	.10	.15	.04	.15	.07	.11
9. DSC RT	.17	.20	−.06	.09	.01	.08
10. DDC RT	.06	.09	−.09	.06	−.04	.05
11. P&P NI	.09	.19	.17	.28	.21	.26
12. P&P PI	−.00	.10	.07	.21	.16	.24
Sentence Verification						
13. True Aff. RT	.23	.25	.03	.07	.08	.07
14. False Aff. RT	.24	.24	−.01	.03	.07	.02
15. True Neg. RT	.23	.24	.03	.00	.00	−.01
16. False Neg. RT	.22	.22	−.01	.05	.04	.01
17. P&P Sec. 2 & 4	.07	.12	.13	.22	.15	.12
18. P&P Sec. 3 & 5	.13	.16	.13	.21	.17	.10
Psychometric Tests						
19. Esoteric Analogies	−.12	−.12	.05	.04	.10	−.01
20. Vocabulary	−.14	−.11	−.00	−.10	.00	.02
21. General Information	.09	.04	.15	.19	.29	.19
22. Remote Associations	−.03	−.01	.17	.06	.04	.02
23. Common Analogies	.13	.06	−.08	−.14	−.12	−.09
24. Matrices	.21	.21	.14	.16	.13	.25
25. Letter Series	.00	−.00	−.12	.01	.03	−.05
26. Figures	.45	.44	.48	.55	.58	.52
27. Cubes	.51	.47	.57	.61	.57	.57
28. Card Relations	.47	.44	.52	.59	.63	.57
29. Paper Folding	.25	.19	.25	.25	.25	.22
30. Surface Development	.50	.44	.49	.51	.55	.47
31. Form Board	.44	.43	.55	.49	.56	.60
32. Identical Pictures	−.11	−.03	.15	.16	.12	.13
33. Finding A's	−.05	−.03	−.05	.10	.13	.12
34. Cancelling Numbers	.12	.20	.23	.26	.18	.20

APPENDIX A (*continued*)

	7.	8.	9.	10.	11.	12.	13.	14.
1.								
2.								
3.								
4.								
5.								
6.								
7.	1.00							
8.	.91	1.00						
9.	.85	.85	1.00					
10.	.86	.83	.92	1.00				
11.	.50	.56	.50	.42	1.00			
12.	.53	.53	.53	.51	.88	1.00		
13.	.56	.56	.54	.52	.41	.49	1.00	
14.	.53	.51	.54	.51	.39	.46	.94	1.00
15.	.48	.45	.48	.45	.33	.39	.84	.87
16.	.47	.46	.46	.44	.36	.42	.88	.91
17.	.51	.54	.46	.45	.69	.72	.75	.72
18.	.49	.47	.40	.40	.60	.66	.72	.72
19.	.12	.00	.06	.13	−.02	.13	.15	.17
20.	.08	−.07	.00	.12	−.07	.08	.25	.24
21.	.13	.07	.08	.19	−.03	.08	.04	.06
22.	.10	.05	.04	.12	.13	.23	.14	.16
23.	.03	−.07	.02	.00	−.06	−.05	.11	.13
24.	.11	.26	.22	.19	.14	.20	.00	−.03
25.	−.09	.02	.02	−.02	.04	.08	.01	−.02
26.	.09	.11	.14	.13	.31	.23	−.03	−.03
27.	.08	.09	.12	.11	.27	.30	.16	.18
28.	.20	.23	.24	.22	.24	.19	.05	.04
29.	−.13	−.15	−.06	−.09	−.11	−.05	−.02	−.02
30.	−.08	−.10	−.02	−.11	.04	.02	−.06	−.05
31.	−.08	−.09	−.03	−.03	.04	.02	−.10	−.12
32.	.26	.17	.18	.24	.39	.44	−.04	−.06
33.	.24	.26	.28	.31	.45	.51	.17	.15
34.	.29	.30	.31	.26	.52	.54	.33	.32

(continued)

APPENDIX A (*continued*)

	15.	16.	17.	18.	19.	20.
Mental Rotations						
1. Depth RT						
2. Picture Plane RT						
3. P&P Sec. 1						
4. P&P Sec. 2						
5. P&P Sec. 3						
6. P&P Sec. 4						
Letter Matching						
7. NI RT						
8. PI RT						
9. DSC RT						
10. DDC RT						
11. P&P NI						
12. P&P PI						
Sentence Verification						
13. True Aff. RT						
14. False Aff. RT						
15. True Neg. RT	1.00					
16. False Neg. RT	.90	1.00				
17. P&P Sec. 2 & 4	.64	.70	1.00			
18. P&P Sec. 3 & 5	.69	.72	.91	1.00		
Psychometric Tests						
19. Esoteric Analogies	.26	.20	.19	.25	1.00	
20. Vocabulary	.26	.21	.18	.23	.61	1.00
21. General Information	.11	.07	.10	.24	.51	.46
22. Remote Associations	.17	.13	.26	.29	.31	.18
23. Common Analogies	.15	.08	−.03	.02	.19	.29
24. Matrices	−.08	−.04	.11	.11	.13	−.04
25. Letter Series	−.06	−.12	.04	.02	.15	.10
26. Figures	−.06	−.10	.21	.21	.04	.06
27. Cubes	.12	.18	.27	.29	.15	.07
28. Card Relations	.03	−.01	.17	.15	.03	.04
29. Paper Folding	−.08	−.04	−.00	−.02	.12	.08
30. Surface Development	−.07	−.06	−.04	−.00	.15	.05
31. Form Board	−.14	−.14	−.14	−.13	.11	.06
32. Identical Pictures	−.09	−.11	.19	.18	.17	.04
33. Finding A's	.08	.04	.32	.30	.09	.05
34. Cancelling Numbers	.21	.21	.38	.34	−.14	−.14

APPENDIX A (*continued*)

	21.	22.	23.	24.	25.	26.	27.	28.
1.								
2.								
3.								
4.								
5.								
6.								
7.								
8.								
9.								
10.								
11.								
12.								
13.								
14.								
15.								
16.								
17.								
18.								
19.								
20.								
21.	1.00							
22.	.24	1.00						
23.	.09	.12	1.00					
24.	.12	.05	.07	1.00				
25.	.03	.04	.18	.30	1.00			
26.	.21	.08	−.00	.12	−.03	1.00		
27.	.27	.19	−.03	.13	.01	.52	1.00	
28.	.26	.02	.05	.10	.04	.73	.58	1.00
29.	.06	.06	.27	.06	.06	.25	.33	.32
30.	.04	−.00	.10	.15	.11	.50	.56	.50
31.	.22	.02	.17	.07	−.04	.42	.51	.46
32.	−.01	.27	−.09	−.01	.01	.33	.29	.18
33.	.02	.14	.11	.11	.27	.24	.12	.17
34.	.04	.14	−.13	.08	−.10	.24	.20	.12

(continued)

APPENDIX A (*continued*)

	29.	30.	31.	32.	33.	34.
Mental Rotations						
1. Depth RT						
2. Picture Plane RT						
3. P&P Sec. 1						
4. P&P Sec. 2						
5. P&P Sec. 3						
6. P&P Sec. 4						
Letter Matching						
7. NI RT						
8. PI RT						
9. DSC RT						
10. DDC RT						
11. P&P NI						
12. P&P PI						
Sentence Verification						
13. True Aff. RT						
14. False Aff. RT						
15. True Neg. RT						
16. False Neg. RT						
17. P&P Sec. 2 & 4						
18. P&P Sec. 3 & 5						
Psychometric Tests						
19. Esoteric Analogies						
20. Vocabulary						
21. General Information						
22. Remote Associations						
23. Common Analogies						
24. Matrices						
25. Letter Series						
26. Figures						
27. Cubes						
28. Card Relations						
29. Paper Folding	1.00					
30. Surface Development	.47	1.00				
31. Form Board	.31*	.52	1.00			
32. Identical Pictures	−.04	.13	.19	1.00		
33. Finding A's	−.12	−.06	.11	.35	1.00	
34. Cancelling Numbers	−.10	.02	.13	.23	.30	1.00

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