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Cognitive Correlates of General Intelligence: Toward a Process Theory of *g*

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The cognitive correlates literature suggests that a general ability, probably Spearman's *g*, underlies most information processing/intelligence relationships. In the present paper we suggest that the nature of *g* is clarified by the following patterns: (a) response consistency has better predictive and convergent validity than does response speed, and (b) tasks which demand dynamic memory processing predict intelligence better than do tasks which require only stimulus encoding and simple stimulus/response translations. Accordingly, *g* appears related to the ability to flexibly and consistently reconfigure the contents of working memory. A possible physiological basis of this ability is the recruitment of the transient neural assemblies which underly *thought* (after Hebb, 1949).

BACKGROUND

In "cognitive correlates" research, one attempts to identify the information processing skills (e.g., memory retrieval, short-term memory search, etc.) that predict psychometric test scores. The goal is to determine, in useful detail, what psychometric tests actually measure (Pellegrino & Glaser, 1979). Although various interpretations of the "correlates" literature exist, we will argue in support of the following views: (a) Information processing/intelligence correlations are not task-specific, rather, they are primarily based on *g;* and (b) the pattern of these correlations suggests the following theory: that *g* depends on the plasticity of a dynamic neural system related to consciousness that must constantly reconfigure to represent shifting perceptual and cognitive events. We begin by indicating why general ability rather than task-specific theories are warranted.

The opinions expressed in this chapter are those of the authors, are not official and do not necessarily reflect the views of the Navy Department.

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Problems with Task-Specific Theories

1. Cognitive Processes Are Rarely Independent. A study by Jensen (1987a), for example, indicates that components from visual search and memory search tasks are correlated, despite being behaviorally dissimilar. Other studies report a general speed factor underlying various reaction time (RT) tasks (Keating & Bobbitt, 1978; Kyllonen, 1985; Levine, Preddy, & Thorndike, 1987; McGue, Bouchard, Lykken, & Feuer, 1984; Saccuzzo, Larson, & Rimland, 1986; also, see Cooper & Regan, 1982), and still more studies show that RTs are intercorrelated (e.g., Jackson & McClelland, 1979; Lansman, Donaldson, Hunt, & Yantis, 1982; Paul, 1984; Vernon, 1983; Vernon, Nador, & Kantor, 1985). These general ability findings argue that information processing is a somewhat generic skill.

2. Process/Aptitude Relationships Are Rarely Specific. Correlations between seemingly diverse verbal and nonverbal tasks are illustrative (e.g., Jenkinson, 1983; Levine, Preddy, & Thorndike, 1987). Paul (1984) for example, reported an overall correlation of 0.44 (correlation reflected) between a verbal RT task (sentence verification, or SV) and a nonverbal psychometric test (Ravens Matrices), while Jenkinson (1983) reported that SV correlated about equally with both verbal and nonverbal measures of intelligence, despite the fact that the SV paradigm used was thought to evoke a linguistic strategy. A relationship between verbal RT tasks and the Raven was also reported by Ford and Keating (1981). Jackson and Myers (1982), in a study on intellectually advanced preschool children, found that a letter-naming task correlated 0.32 and 0.39 with Block Design (a spatial test) and a reading score, respectively, although only the latter correlation was significant. Keating, List, and Merriman (1985), who used a convergent/divergent method reminiscent of Campbell and Fiske's (1959) multitrait-multimethod matrix, found no clear divergent pattern of relationships between various information processing tasks and verbal and spatial aptitude, although it should be noted that Keating et al.'s results were almost entirely negative. Data from Jackson and McClelland (1979) indicate that the name match (NM) portion of the NI-PI test was related to both mathematical and verbal skill (NM with verbal, 0.35, NM with math, 0.37). Conversely, *visual* encoding tasks such as the Hick Paradigm and inspection time correlate with *verbal* performance (Barrett, Eysenck, & Lucking, 1986; Brand & Deary, 1982; Jensen, 1987b; Lubin & Fernandez, 1986). Given these findings, it is not surprising that RTs are sometimes more highly correlated with derived *g* factors from psychometric batteries than they are to specific tests or content factors (e.g., Larson, Merritt, & Williams, 1988; Smith & Stanley, 1987; Vernon, 1983).

While there is occasional evidence for specificity in process/aptitude relationships (e.g., Geary & Widaman, 1987; Sternberg & Gardner, 1983; Vernon, Nador, & Kantor, 1985), such findings are the exception rather than the rule. We thus think it best to adopt the advice of Snow (1979): "The principle of parsimony demands that special ability interpretations be adopted only when general abilities can be ruled out" (p. 118). Results thus far are certainly not sufficient to rule out a general intellectual ability (probably Spearman's *g*) that might largely account for correlations between cognitive processes and psychometric ability measures. We will now focus upon the possible nature of this general ability.

Critical Data for a General Ability Theory

The second part of our argument is that it might be possible to clarify the nature of *g* by examining validity differences among tasks; that is, some types of processing measures correlate well with intelligence, while others correlate poorly, and such patterns might illustrate how *g* is expressed. Of primary importance are patterns related to (a) task complexity and (b) reaction time variability, respectively. These are described below.

1. ***Task Complexity.*** There is much evidence for a validity continuum that parallels the apparent complexity of RT tasks, that is, more complex RT tests show greater correlations with intelligence (Vernon, 1986). This has been noted elsewhere (e.g., Jensen, 1982, 1987c; Mackintosh, 1986), and the conclusion seems supported by data from a number of studies (Frearson & Eysenck, 1986; Goldberg, Schwartz, & Stewart, 1977; Hunt, Lunneborg, & Lewis, 1975; Jackson & McClelland, 1979; Palmer, MacLeod, Hunt, & Davidson, 1985; Payne, Christal, & Kyllonen, 1984). Cohn, Carlson, and Jensen (1985), for example, reported a correlation of .94 between the complexity of RT tasks (as indicated by mean latency) and the magnitude of ability group differences manifest on the task. The theoretical implication, to which we shall return, is that *g* is minimally related to "generic" speed, rather, *g* is primarily related to speed/efficiency during situations that involve information load. This is further indicated by research suggesting that the validity of reaction time tasks for predicting intelligence can be increased by adding a dual task (e.g., concurrent memory load) (Jensen, 1987c; Stankov, 1983).

2. ***Reaction Time Variability.*** Jensen (1982) noted, after studying reaction time data from his own laboratory, that intra-individual variability (the standard deviation of each subject's reaction times) frequently surpassed response speed as a predictor of intelligence. He suggested that such findings were scientifically important, and proposed a theory in which both speed and variability stemmed from oscillations in the neural pathways involved in sensory processing. Following Jensen's (1982) discussion, few theoretical treatments of variability have been published, although empirical evidence for its importance continues to mount. Briefly, when reaction time (RT) studies also report the standard deviation (*SD*) of response time, *SD* measures continue to correlate as well or better with measured intelligence than do RT scores (Barrett, Eysenck, & Lucking, 1986; Carlson & C.M. Jensen, 1982; Carlson, C.M. Jensen, & Widaman, 1983; A.R. Jensen, 1987a; Nettlebeck & Kirby, 1983; Smith & Stanley, 1983; Vernon, 1983; Vernon, Nador, & Kantor, 1985).

The variability/intelligence relationship does not appear to be a function of extreme scores. Barrett, Eysenck, & Lucking (1986), for example, calculated various RT parameters from the Hick paradigm both before and after the exclusion of extreme response times. Standard deviations of the corrected RT distributions correlated more highly with IQ scores than did *SD*'s from the raw data. Also, the finding is not task-specific: Relationships with intelligence, equal to or exceeding those between RT and IQ, have been reported for variability scores from simple RT (Baumeister & Kellas, 1968), the Hick RT test (Vernon, 1981; Barrett, Eysenck, & Lucking, 1986; Jensen, 1982), a semantic verification test (Jensen, Larson, & Paul, 1988), visual and memory search paradigms (Jensen, 1987a), and various other reaction time tasks (e.g., Vernon, 1983; Vernon, Nador, & Kantor, 1985). As was the case with task complexity, correlations for variability scores imply that the intellectually important aspect of information processing is not pure speed (Jensen, 1987a).

PURPOSE

We have thus far argued that (a) information processing is a generic skill that is in some manner related to psychometric *g*, and (b) validity patterns indicate that task complexity and RT variability are potentially important issues for a theory of *g*. We say *potentially* because certain issues remain to be addressed before we can proceed with our third goal, which is to proffer a theory on the possible nature of *g*. First, it has yet to be demonstrated that these validity differences stem from true aptitude relationships rather than differences in task reliabilities (e.g., measurement error). Thus, one goal of the present study is to compare disattenuated validities. Second, while predictive validity is the focus of most cognitive correlates research, convergent validity must also be addressed. The issue of convergent validity is important because if RT variability, and the ability to perform complex tasks, are both valid information processing measures of *g*, then variability/complexity indices should converge. We examine several aspects of convergent validity in our study.

METHOD

Two studies were conducted with batteries of chronometric and psychometric tests. The first involved university students, while Navy recruits were used in the second. In both studies, (a) reaction times tests were programmed to exclude extreme response times that might distort results, and (b) composite reaction time

(RT) and standard deviation (*SD*) scores were derived by standardizing and summing performance across tasks. We should also note in the overview that little had to be done to "clean" the data. No RT task in either study produced more than a half-percent of excluded responses, and no RT task produced less than a 96% mean accuracy rate.

EXPERIMENT 1

Subjects

The subjects in the test-retest study were 74 volunteer San Diego State University students from an introductory course in psychology. The mean age of the sample was 21.32 years of age, with a standard deviation of 3.57. There were 35 males and 39 females in the sample; 57 were Caucasian, 7 Hispanic, 1 Black, and 4 Asian.

Procedure

1. Computer Administered Tests. The computer tests were presented on IBM PC/XT microcomputers with color monitors and standard keyboards. No special add-ons were used other than color labeling of response keys, and anti-glare filters for the monitors. The order of test presentation was selected for each subject according to prearranged random sequences. The subjects were tested twice, within a period of 1 to 10 days.

1.1. Reaction Time Paradigms. Two reaction time paradigms were used: (a) Hick Paradigm with 1, 3, and 5 choices, and (b) The Arrows Test.

Hick Paradigm. This paradigm is a computer presented version of a task used by Jensen (1982). A horizontal arrangement of lights was presented at the bottom of the CRT (video) screen, and both the space bar and the top row of keys on the keyboard (one key directly below each stimulus light) were used for responding, as described below. All subjects were presented with 1-, 3-, and 5-choice conditions, with order being randomized across subjects. Open squares on the CRT screen were used as stimulus lights, and subjects were instructed to respond by pressing the appropriate key as quickly as possible after a square became illuminated. There were 21 trials at each condition. At the beginning of each trial, the subject rested the forefinger of his dominant hand on the space bar at the bottom of the keyboard. After a random period of time of 1.5 to 2.5 seconds, one of the stimulus squares was illuminated. When the square was illuminated the subject had to (1) press the space bar where his hand was resting, then (2) reach up and press the key directly below the illuminated light. Reaction time was the number of ms (milliseconds) between the onset of the stimulus and the instant the subject pressed the space bar. Movement time was the interval between pressing the space bar and pressing the response key. If a reaction time greater than 2 s was recorded, the trial was discarded and a new one presented to maintain a total of 21 trials per condition. For this and all the RT tests we shall describe, however, less than .01% of all trials across subjects were actually discarded. Median reaction time for 1-, 3-, and 5-choice conditions were used in subsequent analyses, along with the standard deviation of the 21 "good" trials from each condition.

The Arrows Test. In the Arrows test (Larson, 1985), subjects were instructed to fixate on two small circles (the lowercase letter "o") presented 0.5 horizontal inches apart in the center of the CRT screen. For each trial, one of the circles was replaced by an arrow, and, depending on the arrow's direction and position, the subject responded by pressing either a right or left key on the microcomputer keyboard. If the arrow pointed down, its position indicated the appropriate response. For example, if a down-pointing arrow replaced the right circle, the right key was pressed. If an arrow pointing right or left was presented, then its direction became the relevant cue while position became a distractor. For example, if an arrow appearing on either side pointed right, the right key was pressed. The position and direction of the arrow were varied randomly. The test involved 82 trials; 41 with downward arrows and 41 with right-left arrows. Based on our a priori judgments about probable response times, the test administration software was written so that reaction times greater than 2 s were discarded and new items presented to maintain a constant number of trials per subject. A count was kept of discarded trials. Median response latencies for downward and right-left arrows were included in subsequent analyses, along with an overall standard deviation.

1.2. Inspection Time Paradigms. There were two inspection time tasks: (a) Inspection Time with lines (IT), and (b) the Inspection Time-Perceptual Organization Test (IT-PO Test). Accuracy scores from these tests were standardized and summed to produce a composite IT score. For both inspection time tasks, a visual stimulus was briefly presented. Immediately following stimulus termination, a backward visual noise mask was presented. The mask is known to limit the duration of the sensory signal delivered to the central nervous system (Felsten & Wasserman, 1980). The subject's task was to make a forced-choice discrimination by pressing one of two keys on the microcomputer keyboard. Final score was the total number of correct responses. Each IT task is briefly described below.

Inspection Time Test (IT). In this task, subjects are briefly shown two horizontal lines of unequal length, presented in the center of the CRT screen. For each trial, the task is to determine which line in the pair is longer. Following each response, subjects are given computer-generated performance feedback. The display of the test lines is terminated by presentation of a spatially overlapping line, or "mask," which obscures the test items and limits the viewing time. Stimulus duration is thus the chief source of item difficulty. Five stimulus durations were used; 16.7, 33.4, 66.8, 100.2, and 150.3 ms. These durations were chosen (based on our previous research) to provide an adequate range of item difficulty, including a likely floor and ceiling for our particular subjects. There were 10 trials per duration, presented in order of a prearranged random sequence. The test thus consisted of 50 trials. The length of the test lines were 17.5 mm and 14.3 mm.

Inspection Time Test-Perceptual Organization (IT-PO). The Perceptual Organization (PO) test is a variation of inspection time where a discrimination must be made between briefly displayed patterns of dots organized into either rows or columns. The technique itself was inspired by an earlier series of studies concerning a relationship between intelligence and discrimination of tachistoscopically presented patterns (De Soto & Leibowitz, 1956; Krech & Calvin, 1953; Pickrel, 1957). As with the Inspection Time test, stimuli are randomly presented at any one of five display speeds: 16.7, 50.1, 83.5, 167, and 334 ms. Immediately following termination of the pattern display, a spatially overlapping cluster of dots was used to obscure the target item and thus terminate visual analysis. There were 15 trials per display speed, with order of presentation completely randomized. At the beginning of each trial subjects were instructed to attend to a fixation point in the center of the screen. After 1 s, a dot pattern, approximately 16 mm square, was presented next to fixation, offset in the direction of one of the four screen corners, but overlapping with fixation so that one of the corners of the stimulus pattern was anchored to screen center. The pattern was comprised of dots grouped into either 5 rows or 5 columns. The rows or columns were spaced approximately 4 mm apart. Subjects were instructed to respond by pressing an appropriate key, depending on whether they had perceived an upright (columns) or sideways (rows) pattern.

1.3. Machine Paced Items: Mental Counters. Machine-paced tests present the subject with a rapid series of video frames, with each frame containing information critical to on-going cognitive operations. To be successful, subjects must be able to process information at the rate the frames are presented.

Mental Counters. In the Mental Counters Test (Larson, 1986), subjects must keep track of the values of three independent "counters," which change rapidly and in random order. (The difficulty of the task comes from having to simultaneously hold, revise, and store three counter values under severe time pressure. Slow execution of counter adjustments leads to a general breakdown on the task.) The counters are represented as lines on the video monitor (3 side by side 1.0-inch horizontal dashes in the center of the screen). The initial counter values are zero. When a small target (a .25-inch box) appears *above* a dash, the corresponding counter must be adjusted by adding "1." When the target appears *below* one of the three dashes, the corresponding counter must be adjusted by subtracting "1." (See Figure 1). The maximum and minimum counter values used in the test were +3 and −3, respectively. The test items vary both in the number of adjustments and the rate of presentation. There were two levels of counter adjustments (5 and 7) and two levels of rate of presentation (fast and slow). The actual test involved a total of 40 trials. On 20 trials, 5 adjustments were required. Seven adjustments were required on the remaining 20 trials. On 20 trials, adjustments were required at the rate of one every .75 s. On the remaining 20 trials, adjustments were required at the rate of one every 1.33 s. Number of targets and rate of presentation were completely counterbalanced. Total correct was used as the summary score.

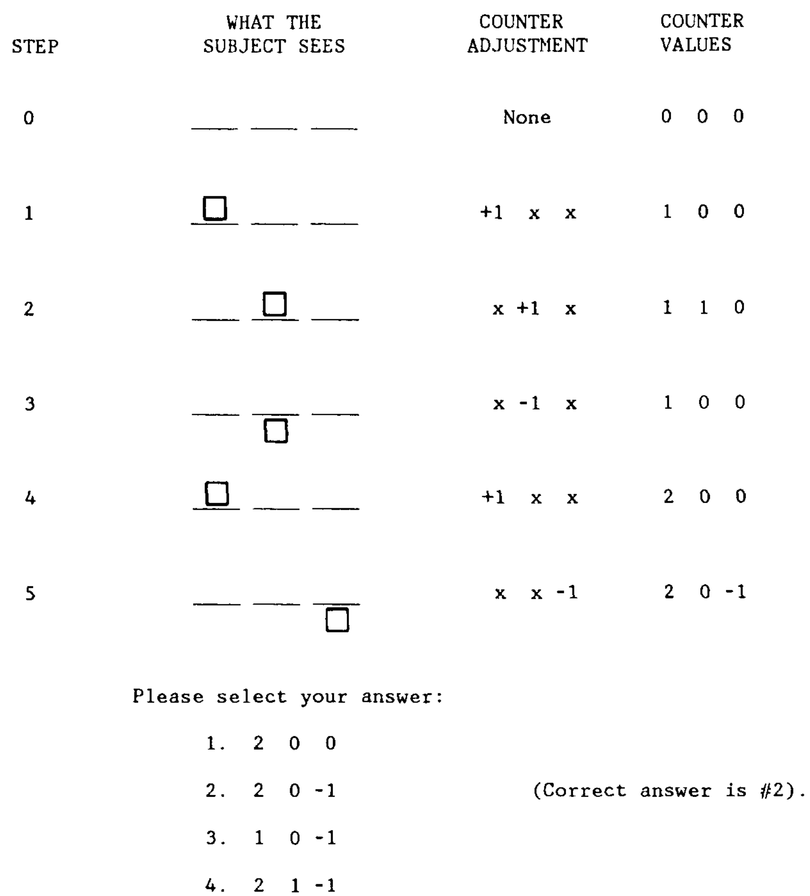

FIG. 1. Sample Item from Mental Counters Test

2. Paper and Pencil Tests. We selected paper and pencil reference markers from spatial, reasoning, verbal, and math ability domains. The tests are:

2.1. The Surface Development (Ekstrom, French, & Harman, 1976). This test loads on a spatial visualization factor, which is defined as the ability to manipulate or transform the images of spatial patterns into other arrangements. In this test, drawings are presented of solid forms that could be made by folding paper or sheet metal. Subjects must determine the relationship between parts of unfolded paper diagrams and the parts of corresponding solid forms. The test was group administered.

2.2. The Raven Progressive Matrices (RPM) Test, Advanced (Raven, 1962) also group administered with a 40 minute time limit. The RPM was originally designed as a nonverbal test of general intelligence.

2.3. In addition, each subjects' scores on the *Scholastic Aptitude Test, Verbal (SATV) and Math (SATM)* were recorded from their official transcripts.

2.4. Psychometric Composite. The four paper and pencil scores were standardized and summed to provide a composite general ability index. We discovered, however, that 34 subjects had no SAT scores on file. A general ability composite could therefore only be calculated for the remaining 40 subjects.

RESULTS

Relationships between information processing and scores on the general ability composite are presented in two separate sections. In the first section, we contrast the disattenuated validities (predictive and convergent) of RT medians and RT standard deviations in order to (a) determine whether the superior predictive validity of *SD*s is due to the constructs or to measurement error, and (b) to determine whether *SD*s and complex information processing paradigms predict one another (i.e., converge). In the second section, we contrast the disattenuated predictive validities of tasks of differing complexity.

Response Medians Versus Standard Deviations

Reliabilities. Reaction times and standard deviations from the various conditions of the Hick and Arrows paradigms were converted to standard scores, then averaged to form RT and *SD* composites. This was done separately for data from the first and second test sessions. Test-retest reliabilities (based on an N of 74) were .86 for the composite RT measure, and .55 for the composite *SD* score. These reliabilities were used to disattenuate correlations with criterion measures (see below).

Predictive and Convergent Validities. All of the analyses which follow are based on the 40 subjects for whom a general ability score could be calculated. (A complete set of raw correlations for these subjects is presented in Appendix One). Table 1 presents the intercorrelations of the criterion measures. The means and standard deviations for each of the criterion variables are also shown. As would obviously be expected, the four paper-and-pencil scores are all well correlated with the psychometric composite since these are part/whole relationships. Correlations between psychometric ability, Counters, and inspection time will be discussed in a later section on task complexity.

The validities for the speed and variability composites are shown in Table 2. Disattenuated correlations (corrected for RT and *SD* reliability) appear in the top row, while the raw correlations, along with their level of significance, are shown below in parentheses. At the right of the table are *z* statistics for tests of differences between correlations, using dependent samples (based on Formula 14.19 in Glass & Stanley, 1970). Looking first at *predictive* validity, variability predicts scores on the psychometric composite significantly better than does speed, and this occurs in spite of, rather than because of, differences in task reliabilities. The difference in validities is quite dramatic; greater, in fact, than that reported by other authors (e.g., Jensen, 1987b). The discrepancy in results could be due to our use of composites, which tend to produce more reliable measures. Our main prediction about *convergent* validity is that variability should predict complex information processing (Mental Counters) better than simple processing (inspection time). This follows from the belief that variability and complex performance are dual indices of the functioning of a generic cognitive system or resource (g). It must also be stressed, however, that the IT and

TABLE 1
Correlations Between Criterion Measures

	Psychometric Composite (1)	Surface (2)	Raven (3)	SATV (4)	SATM (5)	Counters (6)	IT (7)
1.	1.00						
2.	0.76**	1.00					
3.	0.81**	0.65**	1.00				
4.	0.63**	0.17	0.31*	1.00			
5.	0.76**	0.45**	0.50**	0.31*	1.0		
6.	0.59**	0.46**	0.59**	0.24	0.49**	1.0	
7.	0.29*	0.25	0.18	0.27*	0.13	0.16	1.0
M	0.05	31.23	21.74	436.67	500.21	27.44	0.06
SD	2.88	15.13	4.89	80.31	86.60	6.57	0.65

Note. SATV (Verbal); SATM (Math); IT (Inspection Time Composite).
$^{*}p < .05$
$^{**}p < .01$

TABLE 2
Disattenuated and Raw Correlations (In Parentheses) Between Response Times, Standard Deviations, and Criterion Measures

	RT	*SD*	*z*	prob. *z*
Predictive Validity				
Psychometric	−0.16	−0.62		
Composite	(−0.15)	(−0.46**)	−2.591	.01
Convergent Validity				
IT	−0.01	−0.19		
	(−0.01)	(−0.14)	−1.021	ns
Counters	−0.24	−0.47		
	(−0.22)	(−0.35*)	−1.067	ns

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

Counters paradigms (i.e., the criteria) used in the convergent analysis bear little resemblance to RT tasks. Inspection time only requires that subjects accurately perceive the details of a brief display. Mental Counters requires that subjects track information across a series of video frames. In neither case is a speeded response required. In partial confirmation of the hypothesis, the only significant correlation in the convergent analyses is that between variability and the complex Counters task. With a sample size of 40, however, this correlation was not significantly different than that between RT and Counters.

The Counters/*SD* relationship is particularly interesting, for it suggests that performance on a fast, cognitively demanding task depends less on speed than on consistency. Possibly, lapses during sequential operations lead to unrecoverable processing errors, thereby causing performance breakdowns. Correlations between *SD*s and intelligence may stem, in part, from similar errors in working memory, where lapses at various stages of information storage and transformation break the chain of critical problem-solving operations.

Task Complexity

As noted in the introduction, the literature suggests that IQ scores correlate better with complex RT tasks than with simple RT. Though apparently a robust finding, one can still argue that the definition of "complexity" remains problematic. That is, response latency is typically a de facto measure of complexity (e.g., Cohn, Carlson, & Jensen, 1985), since items that take longer are also assumed to be more complex. While this contains an obvious element of truth, a description based on cognitive processes is desirable.

The tasks in the present study fall into three complexity levels, based on the number and type of cognitive operations they require (under an admittedly global analysis). The three levels are incremental, since each subsumes the simpler group or groups, but adds new demands of its own. Based on the predictive/convergent results which showed *SD*s to be more valid than RTs, we used a variability measure of task performance rather than speed wherever a choice was possible.

LEVEL 1: Encoding. The tests at this level (the two inspection time tasks, and the standard deviation of the Hick simple RT condition) require rapid acquisition of sensory data. The combination of IT and RT tasks is justified by the fact that the IT paradigm itself is based on a theoretical data accumulation model similar to that underlying the Hick RT paradigm (see Vickers, Nettlebeck, & Wilson, 1972). Again, we use *SD* rather than RT to be consistent with the results of the predictive/convergent validity analyses. Also, a case for combining *SD* and IT can be made at the construct level; Smith (1986), for example, has argued that ''the relationship of IT with intelligence can be seen as the relationship of stimulus processing variability with intelligence'' (p. 706). Scores for the encoding tasks were standardized and summed, with the sign of the Hick test reversed so that higher sores were consistently associated with better performance. This produced positive correlations with intelligence scores.

LEVEL 2: Encoding + Memory Comparison. At level 2, the stimuli are first encoded, then matched against a set of response rules held in temporary storage. The standard deviation of choice RT (the Arrows test) represents the second level of complexity.

LEVEL 3: Encoding + Memory Comparison + Momentary Workload. At level 3, tasks require greater temporary information storage/handling than at level 2. Such demands can arise from a number of task characteristics, including a larger data set associated with individual items, more data transformations in memory, or cumulative operations in which the product of each problem step must be incorporated into subsequent processes. In the present study, Level 3 is represented by the Mental Counters test, which involves both a large data set and cumulative operations.

Correlations between psychometric ability scores and tasks at the three complexity levels are shown in Table 3 (where ''rxx'' refers to the test-retest reliability for each measure). The only significant validity difference using a two-tailed test is between levels one and three ($z = 2.014$, $p < .05$), that is, between what we have defined as the simplest and most complex tasks. The contrast between levels two and three is, however, significant as a one-tailed test ($z = 1.671$, $p = .0475$). Based on the task requirements of level three (e.g., the Mental Counters test), an important source of validity is probably the momentary workload stemming from accumulation of cognitive data across problem stages. Not to be ignored, however, is the *simultaneous* requirement for encoding, memory com-

TABLE 3
Correlations of Psychometric Composite with Simple and Complex Processing

	Correlation with Psychometric Composite	rxx
1. Encoding	.43 (.28*)	.43
2. 1 + Memory Comparison	−.45 (−.38**)	.70
3. 1 + 2 + Momentary Workload	.77 (.59**)	.59

*$p < .05$
**$p < .01$
***$p < .001$

parison, and other simple behaviors which are not particularly good predictors of general ability when demanded separately. Assuming that each of these processes consumes a small amount of the individuals resources, the combination could perhaps tax the individual's capacity for thought. Thus, there are at least two possible reasons for the superior validity of Counters: (a) The addition of new processes not required by simple tasks, and (b) the combination of processes required by simple tasks. Regardless, an interpretation in terms of increased memory load seems parsimonious. Finally, the partial correlations (based on disattenuated values, and derived via formula 3.3.11 in Cohen & Cohen, 1983) between Level 3 and the psychometric composite, with Levels 1 and 2 separately removed, are .73 and .70, respectively. This is almost equal to the original correlation (.77), and further indicates that variance attributable to the stand-alone tests of simpler processes is not critical to scores on psychometric intelligence tests.

DISCUSSION

The present results confirm that there are theoretically important differences in the validities of information processing tasks. With regard to intra-individual variability, our findings support a study by Jensen (1987a), who determined test-retest reliabilities on 48 university undergraduates. His disattenuated correlations between RT variables and Raven scores indicate that standard deviations were better than RT medians for predicting measured intelligence. Jensen also computed hierarchical factors in which the Raven was first analyzed with RT medians, then, separately, with RT standard deviations. The Raven loaded more highly on the hierarchical variability factor than on the hierarchical speed factor, again supporting the view that, while speed measures often correlate with intelligence, the case for a causal argument is weak. Rather, predictive/convergent validities suggest that the absolute level of performance (mean or median RT) has a weaker relationship with intelligence/processing capacity than does a person's consistency about his or her own level of performance.

The comparison of predictive validities across levels of task complexity again suggests distinct task differences. Tasks with greater memory load show larger correlations with scores on psychometric tests of intelligence, which seems in agreement with earlier studies reported by Stankov (1983) and Jensen (1987c). Both authors report that when the memory load imposed by cognitive tasks was increased, by adding a concurrent (or "dual") task, validities increased. Also, Ackerman's (1986) reaction time research indicates that behavior that has become automatized (e.g., no longer requires active memory representation) seems less correlated with intelligence. Such findings suggest that better prediction of intelligence test scores results when the capacity of the attentional resource (or working memory) system is taxed.

EXPERIMENT 2

The second experiment is essentially a replication of the first experiment, but on a much larger sample of subjects.

Subjects

Subjects were male Navy recruits (N = 343; M age 19.8 years) selected at random from groups undergoing in-processing at the Recruit Training Command, San Diego. Subjects were tested twice on a battery of computerized tests, with (approximately) a one-month separation between sessions. Due to scheduling difficulties, however, only 220 of the subjects were able to return for the retest. This was not a matter of self-selection, since many problems stemmed from our difficulty in obtaining use of the test hall during the narrow window of time in which the recruit's heavy training schedules allowed a retest. There were no "second chances" for obtaining retest scores.

Procedure

1. Computerized Tests

1.1. Reaction Time Paradigms. Two reaction time paradigms were used: The Arrows Test, described in Experiment One, and Simple reaction time.

Simple RT. A .25 inch open square in the center of the CRT screen was used as a stimulus. Subjects were instructed to respond by pressing the space bar as quickly as possible after the square became illuminated. At the beginning of each trial, the subject rested the forefinger of his dominant hand on the space bar at the bottom of the keyboard. After a foreperiod of from 1 to 6 s, the square was illuminated. Reaction time was the number of ms between stimulus onset and the instant the subject pressed the space bar. There were 80 trials. If a reaction time greater than 2 s was recorded, the trial was discarded and a new one presented to maintain a total of 80. A count was kept of discarded trials. Median reaction time was used in subsequent analyses, along with the standard deviation of the "good" trials.

1.2. Inspection Time. The inspection time test was identical to the line comparison task described in Experiment One, except that 15 trials at each of the 5 stimulus durations were presented, rather than 10. The test thus consisted of 75 trials.

1.3. Machine-paced Items. Two machine-paced paradigms were used: (a) The Mental Counters Test, described in Experiment one, and (b) The Numbers Test.

Numbers. The Numbers test is a modification of a preprobed digit encoding task described by Cohen and Sandberg (1980). In our version of the test subjects were given a target digit to remember. Subjects were then asked to observe a rapidly presented sequence of 30 digits (shown one at a time), which included a single instance of the target in the middle third of the sequence (e.g., from serial position 9 to position 19 in the sequence). Following the presentation, the subject's task was to report the number shown before the target digit, the target, and the number after the target. The response was scored as "right" if all three numbers were reported in the correct order, and "wrong" if otherwise. The test was divided into two blocks of 20 trials each. In the first block digits were presented at a rate of one every 0.43 s. In the second block digits were presented at a rate of one every 0.26 s. Total correct across blocks was used as the summary score.

2. Paper and Pencil Tests: Psychometric Composite. Armed Forces Qualifying Test (AFQT) scores were gathered from the recruits' personnel records. The AFQT, which is a composite of verbal and quantitative subtests, is used by the Armed Forces as a measure of general intellectual aptitude/trainability. In addition, the Raven Progressive Matrices (RPM) Test, Advanced (Raven, 1962), was administered with a 40-minute time limit. As noted in Experiment One, the Raven is a nonverbal test designed to measure general intelligence.

Our preliminary analyses show that AFQT and RPM were significantly correlated ($r = .52, p < .01$). Based on the nature of the tests, this finding appears to support the argument that verbal or knowledge-based tests and nonverbal measures of reasoning assess two correlated aspects of general intelligence (e.g., Cattell, 1971). We thus standardized and summed the verbal/quantitative AFQT and the nonverbal RPM for a general ability score, which will be used to represent the construct of psychometric intelligence in the analyses which follow.

RESULTS

The results are again presented in two sections. In the first we continue with the analysis of variability data. In the second section we focus on task complexity. Appendix 2 contains the complete raw correlations for the study.

Response Medians Versus Standard Deviations

Reliabilities. Reaction times and standard deviations from the simple RT and Arrows paradigms were converted to standard scores, then averaged to form RT and *SD* composites. This was done separately for data from the first and second test sessions. Test-retest reliabilities were .76 for the composite RT measure, and .49 for the composite *SD* score. These reliabilities are used to disattenuate correlations with criterion measures (see below).

Predictive and Convergent Validities. Table 4 presents correlations between psychometric and computerized criterion tasks based on the full sample, along with their means and standard deviations. The correlations, which are all significant, will be discussed in greater detail below. Also shown in Table 4 are the reliabilities of the criterion tasks.

The correlations between the reaction time variables and the criterion measures are shown in Table 5. The results from Experiment 1 are reproduced for the sake of comparison. Disattenuated correlations appear in the top row, while the raw correlations, along with their level of significance, are shown below in parentheses. It should be noted that, unlike Experiment One, reliabilities of both predictor and criterion measures were used in correcting for attenuation. Results for *predictive validity* again indicate that a significantly better prediction of psychometric intelligence scores is obtained with variability (*SD*) indices than

TABLE 4
Correlations Between Criterion Measures

	Raven (1)	AFQT (2)	Psychometric Composite (3)	IT (4)	Counters (5)	Numbers (6)
1.	1.00					
2.	0.52	1.00				
3.	0.87	0.87	1.00			
4.	0.19	0.27	0.25	1.00		
5.	0.50	0.44	0.54	0.27	1.00	
6.	0.30	0.36	0.37	0.27	0.42	1.00
M	18.64	57.08	0.01	53.31	26.47	21.42
SD	5.44	20.02	0.87	7.01	7.91	7.16
RELIABILITY	.84	.81	.88	.64	.64	.66

Note. All correlations are significant at $p < .001$.

with response speed indices, though the magnitude of the *SD*/intelligence relationship is smaller than in the first experiment. Comment on the magnitude of the RT/intelligence relationships in Table 5 is also warranted. These correlations (.15 and .17, respectively) are smaller than many in the literature (e.g., Jensen, 1982; Vernon, Nador, & Kantor, 1985), quite probably because the RT tasks themselves are relatively simple. This is, of course, consistent with the argument that complex tasks are the better predictors of intelligence test scores. What must be stressed is that the unusually low RT validities are not the source of the *SD* superiority. RT and *SD* validities both improve as tasks increase in complexity; their relative standing does not change. Therefore, more predictively valid RT tests would yield the same *pattern* of results.

The *convergent validity* analyses replicate the two basic findings of Experiment One: (a) variability is the best predictor of performance on a diversity of information processing tasks, but (b) this finding is more pronounced for "cognitive" tasks (Counters, Numbers) than for simple perceptual tasks (IT). This is all the more interesting when one realizes how behaviorally dissimilar these criteria are from each other, and from RT paradigms, and further suggests that RT variability and complex performance are converging indices of the functioning of a generic cognitive system. Our interpretation is that whatever allows the system to behave consistently also holds cognitive processing together when the sheer volume and pace of information are problematic.

Finally, all seven correlations in Table 5 are higher for the variability score than for the RT score. The binomial probability of this is .0078, again illustrating that these are not chance findings.

Task Complexity

In Experiment One we developed a grouping scheme corresponding to three levels of task complexity. We use the same scheme here. The Numbers test described above was not included, to keep the composites as similar as possible to those in the first experiment.

LEVEL 1: Encoding. Encoding was measured by a composite of IT and the standard deviation of simple RT (using standard scores), with the sign reversed for the latter variable.

LEVEL 2: Encoding + Memory Comparison. As in Experiment One, level 2 was represented by the standard deviation of choice RT (the Arrows RT test).

LEVEL 3: Encoding + Memory Comparison + Momentary Workload. As in Experiment One, level 3 was represented by the Mental Counters test.

Correlations between psychometric intelligence scores and tasks exemplifying the three complexity levels are shown in Table 6. The validities of levels one and

TABLE 5
Disattenuated and Raw Correlations of Response Times and Standard Deviations with Criterion Measures

	RT	*SD*	*z*	prob. *z*
Study One				
Predictive Validity				
Psychometric	−0.16	−0.62		
Composite	(−0.15)	(−0.46**)	−2.591	.01
Convergent Validity				
IT	−0.01	−0.19		
	(−0.01)	(−0.14)	−1.021	ns
Counters	−0.24	−0.47		
	(−0.22)	(−0.35*)	−1.067	ns
Study Two				
Predictive Validity				
Psychometric	−0.21	−0.43		
Composite	(−0.17**)	(−0.28**)	−2.519	.01
Convergent Validity				
IT	−0.32	−0.50		
	(−0.22**)	(−0.28**)	−1.381	ns
Counters	−0.39	−0.70		
	(−0.27**)	(−0.39**)	−2.850	.01
Numbers	−0.31	−0.67		
	(−0.22**)	(−0.37**)	−3.518	.01

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

two are not significantly different. Level three, however, has significantly greater validity than either one ($z = 4.502$, $p < .01$) or two ($z = 4.704$, $p < .01$). Again, the probable source of level three validity is the momentary workload stemming from the accumulation and updating of cognitive data across problem stages. Finally, the partial correlations (following disattenuation) between Level 3 and intelligence scores, with Levels 1 or 2 removed, are .72 and .63, respectively.

GENERAL DISCUSSION

In our introduction we argued, from the literature, that the form of information processing/intelligence correlations suggests a single general ability factor (probably psychometric *g*). We also noted two aspects of cognitive performance that appear relevant to a theory of *g*: (a) High ability subjects are more consistent in rate of processing, and (b) The gap between high and low ability subjects grows wider as tasks involve a greater workload (i.e., volume and pace of information). Logically then, consistency and workload capacity should be empirically related.

TABLE 6
Correlations of Psychometric Composite with Simple and Complex Processing

	Correlation with Psychometric Composite	rxx
Study One		
1. Encoding	.43 (.28*)	.43
2. 1 + Memory Comparison	−.45 (−.38**)	.70
3. 1 + 2 + Momentary Workload	.77 (.59***)	.59
Study Two		
1. Encoding	.42 (.27***)	.46
2. 1 + Memory Comparison	−.45 (−.29***)	.48
3. 1 + 2 + Momentary Workload	.72 (.54***)	.64

The present results suggest that this is indeed the case. The challenge, then, is to integrate these findings into a coherent view of mental ability.

Possibly, working memory capacity resides partly in the ability to consistently succeed in generating and altering the cognitive data required at various processing stages. This implies that *g* is related to the agility of symbol manipulation during dynamic cognitive processing. In other words, more intelligent individuals can more flexibly and consistently reconfigure the "contents of consciousness." If so, a better understanding of intelligence might follow from studying the physiology of thought. Such work, however, is still in its infancy. Following Herb (1949), models of "thought" have tended to incorporate the notion of reverberating cortical circuits, or cooperative assemblies of neurons (e.g., Changeux, 1986; Freeman, 1981; Iran-Nejad & Ortony, 1984; Kissin, 1986). Accordingly, a source of capacity limitations may be the flexibility with which the system can recruit new assemblies (e.g., Shaw, 1978). This might also explain the speed with which a percept is formed, and thereby account for the correlations between working memory and encoding speed.

Pending further research, the explanatory power of the neural assembly framework must be judged by its apparent fit with other data on intelligence. The framework certainly seems compatible with a neurophysiological study by Haier et al. (1988), who reported that subjects scoring high on a general intelligence test (Ravens Advanced Progressive Matrices) had *low* brain energy utilization while taking the test. Haier et al. suggest that subjects who perform well on intelligence tests may have more efficient neural circuits, possibly because of less extraneous activity. Such extraneous activity could also be a source of processing variability, such as we have described.

The neural assembly view of intelligence might also help explain certain performance declines associated with aging. Abilities believed subject to age-related deficits include the theoretically interrelated dimensions of "fluid" intelligence (see Horn, 1980), processing speed/variability (Botwinick, 1984; Cerella, Poon, & Fozard, 1982; Fozard, Thomas, & Waugh, 1976; Salthouse & Somberg, 1982; Stine, Wingfield, & Poon, 1986) and processing capacity (Broadbent & Heron, 1962; Light, Zelinski, & Moore, 1982; Spilich, 1983; Wright, 1981). This constellation of aptitude declines suggests, circumstantially, a broad degeneration in the *dynamic* "consciousness processes" necessary for responding to novel or swift events. While the exact physiological bases of the age deficit remains elusive, possibilities include reduction in synaptic density (Birren, Woods, & Williams, 1979), increases in "neural noise" (Welford, 1984), and changes in cardiovascular functioning (Botwinick, 1984) and cerebral energy metabolism (Smith, 1984). It is quite possible that any or all of these degenerative processes could impair the ability of the system to flexibly recruit/activate the neural underpinnings of thought.

Although the connection is admittedly speculative, the recent finding that infant habituation rates predict scores on later tests of intelligence could also fit within a neural circuit framework. The habituation response, which reflects the waning of attention to a repeatedly presented stimulus (Fagan, 1985; Rose, Slater, & Perry, 1986), can be considered a measure of encoding efficiency—children who rapidly lose interest in a repetitive stimulus are presumably quicker at analysis and/or forming neural models. Interestingly, infants who are rapid habituators have fewer instances of central nervous system dysfunction (Lewis & Baldini, 1979), and also score high on later tests of intelligence (Bornstein & Sigman, 1986; Fagan, 1985; Lewis & Baldini, 1979; Rose, Slater, & Perry, 1986). An interpretation compatible with the views presented here is that infants differ in the ability to accomplish a neural reset of short-term memory (Grossberg, 1980) and thereby form a cognitive analog of the novel, attention-capturing object. If the limiting factors include some aspect of plasticity in the neural assemblies underlying consciousness (such we have described), a relationship to adult intelligence might emerge.

Finally, we return to the subject of individual differences in, for example, young adults. We suggest that tests of general intelligence, the *g* factor described by Spearman (1923) and Jensen (1987c), and even overlapping concepts such as working memory and attentional resources, ultimately refer to the operating power of consciousness. This "power" is based on how efficiently the system functions in a dynamic mode. That is, the system must constantly reconfigure to generate the mental objects or symbols that constitute the flow of thought. The reconfiguration is accomplished through the establishment of new cellular networks or assemblies. The correlations between RT variabilities and intellectual performance suggest that the formation of thought is an irregular and unstable process, and that the degree of irregularity is either a cause or correlate of overall efficiency.

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APPENDIX 1
Raw Correlations for Experiment 1 (N = 40)

	RAVEN	SURFACE	SATV	SATM	COUNTERS	IT	IT-PO	HICK1	HICK1*SD*	HICK3
RAVEN	1.00	0.65**	0.31*	0.50**	0.59**	0.17	0.06	0.09	0.11	0.07
SURFACE	0.65**	1.00	0.17	0.45**	0.46**	0.21	0.13	−0.03	0.00	−0.04
SATV	0.31*	0.17	1.00	0.31*	0.24	0.10	0.31*	0.11	−0.28*	0.14
SATM	0.50**	0.45**	0.31*	1.00	0.49**	0.12	0.06	−0.16	−0.12	−0.05
COUNTERS	0.59**	0.46**	0.24	0.49**	1.00	0.14	0.07	−0.03	0.06	0.05
IT	0.17	0.21	0.10	0.12	0.14	1.00	−0.06	−0.02	−0.02	−0.02
IT-PO	0.06	0.13	0.31*	0.06	0.07	−0.06	1.00	0.06	−0.27*	0.08
HICK1	0.09	−0.03	0.11	−0.16	−0.03	−0.02	0.06	1.00	0.39**	0.57**
HICK1*SD*	0.11	0.00	−0.28*	−0.12	0.06	−0.02	−0.27*	0.39**	1.00	0.06
HICK3	0.07	−0.04	0.14	−0.05	0.05	−0.02	0.08	0.57**	0.06	1.00
HICK3*SD*	−0.48**	−0.50**	−0.21	−0.50**	−0.57**	−0.17	0.03	0.34*	0.14	0.38**
HICK5	−0.01	−0.14	0.08	−0.13	−0.23	−0.11	0.14	0.50**	0.04	0.76**
HICK5*SD*	0.14	−0.18	−0.25	−0.34*	−0.05	0.03	−0.23	0.03	0.06	0.08
ARROW:D	0.00	−0.09	0.04	−0.22	−0.18	−0.07	0.09	0.38**	0.14	0.44**
ARROW:S	−0.19	−0.28*	−0.04	−0.39**	−0.29*	−0.06	0.06	0.40**	0.08	0.38**
ARROW:*SD*	−0.20	−0.33*	−0.18	−0.42**	−0.36*	−0.06	−0.01	0.35*	0.14	0.08

	HICK3*SD*	HICK5	HICK5*SD*	ARROW:D	ARROW:S	ARROW:*SD*
RAVEN	−0.48**	−0.01	0.14	0.00	−0.19	−0.20
SURFACE	−0.50**	−0.14	−0.18	−0.09	−0.28*	−0.33*
SATV	−0.21	0.08	−0.25	0.04	−0.04	−0.18
SATM	−0.50**	−0.13	−0.34*	−0.22	−0.39**	−0.42**
COUNTERS	−0.57**	−0.23	−0.05	−0.18	−0.29*	−0.36*
IT	−0.17	−0.11	0.03	−0.07	−0.06	−0.06
IT-PO	−0.03	0.14	−0.23	0.09	0.06	−0.01
HICK1	0.34*	0.50**	0.03	0.38**	0.40**	0.35*

(continued)

APPENDIX 1 *(Continued)*
Raw Correlations for Experiment 1 (N = 40)

	HICK3*SD*	HICK5	HICK5*SD*	ARROW:D	ARROW:S	ARROW:*SD*
HICK1*SD*	0.14	0.04	0.06	0.14	0.08	0.14
HICK3	0.38**	0.76**	0.08	0.44**	0.38**	0.08
HICK3*SD*	1.00	0.60**	0.40**	0.41**	0.57**	0.50**
HICK5	0.60**	1.00	0.37*	0.66**	0.57**	0.31*
HICK5*SD*	0.40**	0.37*	1.00	0.27*	0.33*	0.33*
ARROW:D	0.41**	0.66**	0.27*	1.00	0.89**	0.65**
ARROW:S	0.57**	0.57**	0.33*	0.89**	1.00	0.76**
ARROW:*SD*	0.50**	0.31*	0.33*	0.65**	0.76**	1.00

*p < .05
**p < .05

APPENDIX 2
Raw Correlations for Experiment 2 (N = 343)

	RAVEN	AFQT	COUNTERS	NUMBERS	IT	SIMPLE RT	SIMPLE *SD*	ARROW:D	ARROW:S	ARROW:*SD*
RAVEN	1.00									
AFQT	0.52**	1.00								
COUNTERS	0.50**	0.44**	1.00							
NUMBERS	0.30**	0.36**	0.42**	1.00						
IT	0.19**	0.27**	0.27**	0.27**	1.00					
SIMPLE RT	−0.16**	−0.15**	−0.25**	−0.21**	−0.20**	1.00				
SIMPLE *SD*	−0.14**	−0.16**	−0.27**	−0.22**	−0.16**	0.58**	1.00			
ARROW:D	−0.10*	−0.19**	−0.22**	−0.20**	−0.21**	0.36**	0.18**	1.00		
ARROW:S	−0.12*	−0.21**	−0.26**	−0.24**	−0.22**	0.37**	0.23**	0.88**	1.00	
ARROWS:*SD*	−0.26**	−0.24**	−0.36**	−0.37**	−0.29**	0.39**	0.32**	0.66**	0.69**	1.00

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