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The Nature of Psychometric *g*: Unitary Process or a Number of Independent Processes?

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This study investigates whether a unitary elemental process or a number of independent elemental processes, as measured by elementary cognitive tasks (ECTs), underlie psychometric *g*. A sample of 101 university students was administered two intelligence tests (Raven's Advanced Progressive Matrices and the Multidimensional Aptitude Battery) and a large battery of ECTs. The results of this study reject the theory that some single or unitary process underlies psychometric *g*. Rather, it appears that individual differences in psychometric *g* may reflect as many as four independent components of variance. These findings support the theory that various complex mental tests correlate highly with each other, giving rise to a psychometric *g* factor, because they require some of the same elemental processes. Further research will be needed to determine precisely the number and nature of these components. It is also important to note that the multiple correlation of *g* regressed on these four components derived from elementary cognitive variables is .542. The maximum correlation possible between the psychometric variables and the battery of ECTs in this study is nearly as high as correlations among various standardized IQ tests themselves (canonical $r = .603$). After correction for the considerable restriction of range on IQ in the sample, the *r* is increased to .722. Hence, this battery of ECTs accounts for approximately half of the phenotypic variance in *g* and probably as much as 70% of the genotypic variance. Moreover, the finding that individual differences in conceptually distinct processes (such as speed of visual search and speed of memory search) are highly correlated indicates the presence of individual differences in some neurological level of processing common to both tasks.

Contemporary research on the nature of psychometric *g* has only just begun to move from descriptive to causal analysis (Eysenck, 1988; Jensen, 1987a). This research, although still correlational, has attempted to identify variables related to *g* outside the realm of psychometric tests, such as the average evoked potential

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(Eysenck & Barrett, 1985), the electroencephalogram (Pollock et al., 1989), glucose metabolism in the brain as expressed by PET scan (Haier et al., 1988), and reaction time (RT) on elementary cognitive tasks (ECTs; Jensen, 1982a, 1982b, 1986, 1987b).

In recent years, the theory that individual differences in mental ability are essentially related to speed of information processing has received increasing attention (see Vernon, 1987). Many different ECTs, ostensibly tapping different stages of processing (such as encoding, STM scanning, and LTM retrieval) have been used to investigate this relationship. Each of these ECTs has been found to have modest, but reliable correlations with *g*, typically in the range of −.20 to −.40. The correlation between each of these ECTs and *g* may, in fact, be somewhat larger after correction for the attenuating effects of restriction of range and measurement error.

These significant findings notwithstanding, many important questions regarding the nature of *g* and its relationship to speed of information processing remain. One important question now facing researchers in this field is whether a unitary process or a number of independent processes underlie psychometric *g* (Detterman, 1987). Mental speed is a contender for the unitary process defining *g*, as the typically modest correlation between any ECT and *g* could be due to a large amount of task-specific variance (i.e., non-*g* variance) in any one ECT. A competing hypothesis is that *g* comprises a relatively small number of independent elementary cognitive processes. According to this theory, complex mental tests correlate highly with each other because they tap all or most of the same elemental processes. Truly basic (i.e., orthogonal) processes would correlate only moderately (although significantly) with mental tests and not at all with each other. Moreover, the greater the number of these basic processes, the lower their respective correlations with mental tests.

RELATIONSHIPS AMONG ECTs

Some research has been done addressing the relationships among speed-of-information-processing paradigms (e.g., Jensen, 1987c; Keating & Bobbitt, 1978; Lally & Nettelbeck, 1977; Larson & Saccuzzo, 1989; Levine, Preddy, & Thorndike, 1987; Vernon, 1983). These studies attempted to determine whether ECTs are intercorrelated and whether there is a general mental speed factor among them. Taken as a whole, the results of these studies suggest that the various ECTs used to investigate *g* do share some modest amount of variance (roughly 30%), but that group factors among ECTs also exist. The study by Larson and Saccuzzo (1989) also represents an initial attempt to explain this relationship.

The results of these investigations do not, however, determine whether a unitary process or a number of independent processes underlie psychometric *g*. Jensen (1987a) first discussed a test of these competing hypotheses. Jensen's reasoning is as follows: If two or more completely uncorrelated variables, for example, A, B, C, and so on, are all significantly correlated with another variable, X, then X cannot be a unitary variable, but must contain within it components of variance in common with the independent variables A, B, C, and so on. Hence, this hypothesis can be tested by first obtaining a set of orthogonal (i.e., independent) variables based on the measurements from the ECTs. If, then, it is possible to combine perfectly orthogonal variables derived from various ECTs in a stepwise multiple regression so that each independent variable adds a significant increment to the multiple R in the prediction of g, it necessarily follows that the psychometric g cannot reflect a single or unitary process.

EXPERIMENTAL PROCEDURES

Psychometric Tests

Raven's (1966) Advanced Progressive Matrices (APM). The APM is a nonverbal test of reasoning. Under nonspeeded test conditions, the APM has consistently been shown to be a good marker test of Spearman's g (Jensen, 1987b). The APM was administered with the standard instructions, and subjects were told to take all the time they needed to do all of the items.

Multidimensional Aptitude Battery (MAB). The MAB (Jackson, 1984) is a strongly g-loaded multiple-choice test that can be group administered. The MAB consists of 10 subtests and provides Verbal, Performance, and Full-Scale IQ scores. The MAB has been found to be a good measure of general mental ability (Vernon, 1985; Wallbrown, Carmin, & Barnett, 1988, 1989). Subjects were given the standard instructions for the MAB under timed conditions. Vernon and his colleagues determined that correlations between g and many ECTs are unrelated to administration of the MAB under timed or untimed conditions (Vernon & Kantor, 1986; Vernon, Nador, & Kantor, 1985).

Chronometric Apparatuses

For each of the ECTs, subjects were instructed to perform as fast as they could without making errors. Subjects were also given as many practice trials on the ECTs as they desired before beginning testing.

The Hick and Odd-man Paradigms. The Hick paradigm, named after Hick's law (1952), measures both simple and choice RT. Hick's law states that RT increases linearly as a function of the logarithm of the number of choice alternatives (n), usually scaled in bits (i.e., $\log_2 n$, or the amount of information needed to reduce stimulus uncertainty by half). The Odd-man-out paradigm (Odd-man) is essentially a measure of spatial discrimination.

The apparatus used for both the Hick and the Odd-man paradigms, which is very similar to the original Jensen apparatus (first described in Jensen & Munro, 1979), consists of a 13 × 17 inch console tilted at a 30° angle. The "home button," a black push button 1 inch in diameter, is located at the lower center of the panel. The response buttons are an array of eight green push buttons, .5 inch in diameter, which can be illuminated. They are arranged equidistantly from the home button in a semicircle with a 6-inch radius. Plastic flat black overlays can be fastened to the console exposing different push button combinations. Normally exposed are the set sizes of 1, 2, 4, and 8 push buttons (corresponding to 0, 1, 2, and 3 bits). In this experiment, however, only the 0-bit and 3-bit conditions were administered, as ample evidence exists supporting the linear relationship between RT and the number of bits exposed (see Jensen, 1987d).

For the Hick paradigm, a single trial consists of: (1) the subject depresses the home button; (2) an auditory warning signal (a "beep" of 1-s duration) is presented; (3) following a random interval of 1 to 4 s, one of the push buttons is illuminated; (4) the subject, as quickly as possible, removes his or her finger from the home button and depresses the push button that has gone on. The apparatus allows the separate measurement of RT and movement time (MT). RT is the amount of time it takes the subject to lift a finger off the home button after one of the push buttons has been illuminated. MT is the interval between releasing the home button and depressing the pushbutton. RT and MT are recorded in milliseconds by two electronic timers.

The apparatus and procedure used for the Odd-man paradigm are identical to that described for the Hick paradigm, except that instead of one push button going on, three push buttons are illuminated simultaneously. Two of these push buttons are closer together than the third. The subject must depress the one push button that is farther away from the other two. RT and MT are recorded in milliseconds by two electronic timers.

Inspection Time Paradigm. Inspection Time (IT) is the only index of mental speed that does not involve either motor (output) components or executive cognitive processes (metaprocesses). IT is held to tap individual differences in the "speed of apprehension": the quickness of the brain to react to external stimuli prior to any conscious thought (Kranzler & Jensen, 1989).

The IT apparatus consists of a 16.5 × 9.5 inch gray metal box, the front side of which is black. Flush with the face of the apparatus are two vertical columns of multiple-segment red bar light-emitting diodes (LEDs) 6 inches in length, 1.5 inches apart. Connected to the apparatus are two 4.75 × 2.5 inch push button boxes. In the middle of each push button box is a pushbutton .375 inch in diameter. The IT apparatus is interfaced with an IBM-AT computer.

For the IT paradigm, a single trial consists of: (1) an auditory warning signal (a "beep" of 1-s duration) is presented; (2) following a random interval of 1 to 3 s, both of the parallel columns of LEDs go on, one of which is 30% longer than the other; (3) almost immediately after the LEDs go on, both columns of LEDs go on completely (this backward masking stimulus is presented to limit the amount of processing from stored traces); and (4) the subject indicates which line (left or right) is longer by depressing the corresponding (left or right) push button. IT is defined as the minimum exposure duration that is necessary for the subject to discriminate reliably between the two lines.

The total number of trials and the specific exposure durations of the stimuli for each trial are determined by the BRAT algorithm, a heuristic procedure for measuring IT to 2-ms resolution and 90% accuracy. Briefly, the BRAT algorithm has three phases: the first phase provides a quick estimate of IT, starting well above the subject's IT and decreasing in relatively large increments (10 ms after the stimulus exposure duration is under 100 ms) until at least 90% accuracy has been attained in the last 10 trials; the second phase refines this measure by overshooting the initial IT estimate by 30 ms and then slowly increasing (in 6-ms steps) the stimulus duration until at least 90% has been attained in the last 10 trials; the third and final phase overshoots the IT estimate provided by the second phase by 20 ms and then increases the stimulus duration (in 2-ms steps) until the subject makes nine consecutive responses. The exact number of trials and time to administer this test varies (according to resolution of the IT), but typically requires fewer than 100 trials and takes about 5 min.

The IT apparatus allows the separate measurement of IT and decision time (DT). DT is the amount of time it takes the subject to depress the push button after presentation of the backward masking stimulus. IT and DT are recorded in milliseconds by two electronic timers.

Visual Search, Memory Search, and Posner Paradigms. The memory search (MS) paradigm measures the speed of scanning information in short-term memory. The visual search paradigm, a measure of the speed of visual search (VS), is essentially the inverse of the MS paradigm. The Posner paradigm is a measure of the speed of retrieval of overlearned information from long-term memory.

The VS, MS, and Posner paradigms are conducted on an IBM–PC computer with a monochrome monitor. Interfaced with the computer is a 10 × 6.5 inch binary-response console. The home button, a black push button 1 inch in diameter, is located at the lower center of the console. The response buttons are two green push buttons, also 1 inch in diameter, arranged equidistantly from the home button (2.5 inches). The response buttons were labeled *Yes* and *No* for the VS and MS paradigms and for the same–different (S–D) condition of the Posner paradigm. They were labeled *Syn* and *Ant* for the synonym–antonym (S–A) condition of the Posner paradigm. The apparatus allows the separate measurement of RT and MT for each of the paradigms. RT and MT are recorded in milliseconds by two electronic timers.

1. For the MS paradigm, a single trial consists of: (a) the subject depresses the home button; (b) an auditory warning signal (a beep of 1-s duration) is presented; (c) after a 1-s interval, a string of 1 to 7 digits is presented for 2 s;

(d) after a blank random interval of 1 to 4 s, a single probe digit is presented; and (e) the subject, as quickly as possible, indicates whether the probe digit was present in the string of digits by releasing his or her finger from the home button and depressing the appropriate push button (*Yes* if the probe digit was present, *No* if not).

2. The VS paradigm is essentially the opposite of the MS paradigm. In this paradigm, the probe digit is presented first, followed by the presentation of the string of digits, which remains on the screen until a response is made.
3. The Posner paradigm consists of two separate ECTs. In each, the subject is presented with 100 pairs of highly common words[1] and asked to judge whether they are the *same* or *different* according to the criteria of each respective ECT. In the first ECT, same–different (S–D), the word pairs are physically the same (e.g., *car–car*) or different (e.g., *car–jar*). In the second ECT, synonyms–antonyms (S–A), the word pairs are either synonyms (e.g., *fast–quick*) or antonyms (e.g., *hot–cold*).

   In both of these ECTs, a single trial consists of: (a) the subject depresses the home button; (b) an auditory warning signal (a beep of 1-s duration) is presented; (c) after a random interval of 1 to 4 s, a word pair is presented; and (d) the subject, as quickly as possible, indicates whether the word pair is the *same* or *different* by releasing his or her finger from the home button and depressing the appropriate push button (*Yes* if the words are the same, *No* if not).

Subjects and Test Procedures

Subjects in this study were 101 students (52 women, 49 men) at the University of California, Berkeley. Their ages ranged from 17 to 25 years (M = 20.3, SD = 1.79). Subjects were recruited as paid volunteers through an advertisement in the campus newspaper.

Subjects were tested in two sessions, each lasting approximately 1 to 2 hrs. The two psychometric tests were administered in the first session to small groups of subjects (maximum of 4 per group). The second session consisted of the individual administration of the seven ECTs. Administration of the ECTs in a complete Latin-square design was impossible due to that fact that several of the computer programs for the ECTs are written in predetermined order. For example, in the Posner paradigm, the S–D task always precedes the S–A task. Therefore, subjects were randomly assigned to one of the following four orders of ECT administration:

1. Hick/Odd-man, VS/MS, IT, Posner
2. MS/VS, IT, Posner, Hick/Odd-man

[1] According to the Thorndike and Lorge (1944) word count.

3. IT, Posner, Hick/Odd-man, VS/MS
4. Posner, Hick/Odd-man, MS/VS, IT

RESULTS

Results are presented in two sections. The first section describes the descriptive statistics for all of the variables, both chronometric and psychometric. The second section presents results of the various correlational analyses used to test the main hypothesis. In this study, the descriptive statistics are not only of little importance compared to the results of the correlational analyses, but they are also generally consistent with those results obtained from similar samples of university students. Nevertheless, the descriptive statistics for both sets of data are briefly discussed in the following and presented in the Appendix. Last, the results of several preliminary analyses, presented in Kranzler (1990), revealed that the effects of age, ECT administration order, and speed–accuracy trade-off on the chronometric and psychometric variables used in this study are negligible.

DESCRIPTIVE STATISTICS

Psychometric Variables

The descriptive statistics for the raw scores of the APM and the MAB and their corresponding scaled scores are presented in Table A–1 of the Appendix. The scaled scores for the APM are derived from a study equating the APM with the nationally standardized Otis-Lennon IQ test (Jensen, Saccuzzo, & Larson, 1988). The mean MAB full-scale score is 120 and the mean APM scaled score is 118. These scores are well above average in comparison to the standardized sample, both falling around the 90th percentile. The MAB subtest scaled scores, expressed in *T* scores ($M = 50, SD = 10$), range from 62.47 to 51.83, with a mean of 58.10. The sample is also rather restricted in range. The mean standard deviations for the MAB Verbal, Performance, and full scale are 9.88, 12.24, and 10.88, compared to a standard deviation of 15 in the general population. The average standard deviation of the APM is 9.97, compared to 16 in the population.

Chronometric Variables

At least four chronometric variables were measured on each subject for each ECT, except IT. These are: RT median (RTMDN), RT standard deviation over trials (RTSD), MT median (MTMDN), and MT standard deviation (MTSD). For the VS and MS paradigms, the slopes and intercepts from the regression of RT and MT on setsize were also obtained. IT was the only variable measured for the IT paradigm.

Table A–2 displays the descriptive statistics for the Hick and Odd-man paradigms. For the 0-bit condition of the Hick paradigm, procedural errors led to the discarding of the error data for three subjects. Complete data sets were obtained for the Hick 3-bit condition and for the Odd-man ($N = 101$). For both the Hick and Odd-man paradigms, the means and standard deviations for the RT and MT medians and the intraindividual variabilities are consistent with those obtained from similar samples of university students (Frearson, Barrett, & Eysenck, 1988; Frearson & Eysenck, 1986; Jensen, 1987b).

In Table A–3 the descriptive statistics for the Posner paradigm are presented. As can be seen, the medians and intraindividual standard deviations are larger for the S–A task than for the S–D task, the greatest of which is the RTMDN (S–A $M = 915.50$, S–D $M = 683.07$).

Table A–4 displays the descriptive statistics for the MS and VS paradigms. For the MS paradigm, the descriptive statistics are based on a sample size of 100 due to an error in test administration. The degree of fit (Pearson correlation) for the regression of RTMDN on set size is +.99, indicating that the RTMDNs increase as a linear function of set size. For the VS paradigm, the degree of fit for the regression of RTMDN on set size is +.90.

Table A–5 presents results of the IT paradigm.

CORRELATION ANALYSES

The zero-order correlations between the ECT variables are presented in Table A–6 of the Appendix. These correlations vary considerably, ranging from +.95 to −.45, with a median of +.17. The highest intercorrelations are typically between variables in the same paradigm or between variables measuring theoretically comparable information-processing components. The RT, MT, and standard deviation measures also tend to correlate more highly with the same parameters of the other ECTs. The variables that correlate negatively with one another are typically those that are not experimentally independent, namely, the RT and MT slopes and intercepts of the VS and MS paradigms. A negative correlation between intercept and slope is a mathematical artifact due to correlated errors of measurement.

A principal components analysis of the ECTs was conducted to derive orthogonal component scores. All principal components with eigenvalues greater than 1 were retained. Table 1 presents the results of this analysis. These 10 components account for about 28% of the total variance in the 37 ECT variables.

The intercorrelations among the psychometric tests are displayed in Table A–7 of the Appendix. These correlations, which range from +.566 to +.036 with a median of +.250, typify the phenomenon of positive manifold. The Schmid-Leiman (1957) approach to factor analysis was used to extract a general factor (psychometric *g*) from the intercorrelations. The results of this analysis are shown in Table 2. This procedure orthogonalizes the entire factor hierarchy. The factors are thus uncorrelated both between and within factor levels. The psychometric *g* shown here is a second-order factor at the apex of the factor hierarchy. All of the psychometric measures load substantially on *g*. These loadings range

TABLE 1
Loadings of All Elementary Cognitive Tasks[a] (ECTs) on the 10 Principal Components[b]

ECT	Principal Component 1	2	3	4	5	6	7	8	9	10
	249	−006	214	488	−153	183	−223	178	−027	−492
0RTMDN	626	108	−284	144	−238	015	−225	−038	−004	−214
0RTSD	425	060	−048	300	−372	116	071	−285	481	−033
0MTMDN	562	−510	−147	−044	263	054	114	−219	−034	126
0MTSD	−110	243	282	036	−421	278	071	−221	−193	493
3RTMDN	742	313	−322	102	−052	095	−141	−009	023	−114
3RTSD	487	139	−084	247	−001	550	027	046	206	124
3MTMDN	702	−517	−075	−043	140	076	003	116	003	022
3MTSD	−260	302	294	321	−196	−022	209	247	092	171
DRTMDN	490	570	−199	112	185	147	−228	116	−079	−065
DRTSD	−343	456	023	062	402	240	−334	077	−258	044
DMTMDN	627	−616	061	027	145	097	022	−098	015	−062
DMTSD	−045	−005	564	164	−324	351	049	106	035	109
-DRTMDN	510	591	−120	−047	−058	−204	141	096	177	045
-DRTSD	020	138	101	199	134	−299	035	448	455	004
-DMTMDN	541	−545	281	−030	231	−042	−096	−071	069	004
-DMTSD	147	172	135	060	−052	−221	−456	237	−111	379
-ARTMDN	422	691	−148	018	159	151	256	155	012	123
-ARTSD	280	267	096	−090	384	177	−096	358	010	217
-AMTMDN	363	−678	432	−120	050	−130	−227	022	074	038
-AMTSD	266	−409	372	−103	−120	−314	−092	262	005	−041
SRTMDN	680	548	069	−059	−071	−154	174	−012	−128	−012
SRTSD	194	109	679	464	236	−115	088	−249	−140	−092
SMTMDN	698	−525	008	024	008	074	261	191	−074	071
SMTSD	266	518	545	338	202	−195	056	−293	−139	−086
SRTMDN	726	508	063	−125	−100	−177	004	032	−006	042
SRTSD	329	066	411	−643	−137	223	−197	−109	237	−089
SMTMDN	739	−522	−039	031	023	058	160	021	−002	021
SMTSD	417	463	335	−589	−140	070	−185	−089	193	−068
SRTSLP	108	512	243	−319	198	240	212	068	−186	−181
SRTINT	715	312	−065	128	−177	−343	052	−063	−038	104
SMTSLP	−079	−388	202	−124	−277	226	278	446	−225	−247
SMTINT	766	−438	−060	063	077	001	182	065	−033	147
SRTSLP	176	441	146	−290	225	−183	424	−029	093	−096
SRTINT	705	326	−028	015	−260	−108	−233	049	−073	085
SMTSLP	−323	−078	164	162	482	185	−021	−021	408	093
SMTINT	721	−492	−107	−022	−173	−006	185	047	−078	−024
Var.	8.78	6.45	2.50	2.01	1.80	1.48	1.36	1.24	1.08	1.03

[a]The first two letters in each variable identify the ECT paradigm, which are: Hick 0 bits (H0), Hick 3 bits I3), Odd-man (OD), Same–Different Word Pairs (S–D), Synonym–Antonym Word Pairs (S–A), Memory :arch (MS), and Visual Search (VS). The remaining (four or five) letters in each variable identify the ECT easure: Reaction time median (RTMDN), reaction time standard deviation (RTSD), movement time median ITMDN), movement time standard deviation (MTSD), reaction time slope (RTSLP), reaction time intercept .TINT), movement time slope (MTSLP), and movement time intercept (MTINT).

[b]Decimals are omitted in the component loadings.

TABLE 2
Loadings of the Psychometric Tests on the Schmid-Leiman Hierarchical Factors

	Hierarchical Factors		
Mental Tests	***g***	**Performance**	**Verbal**
Raven's APM	.442	.482	−.061
Information	.602	.072	.501
Arithmetic	.512	−.065	.557
Comprehension	.367	.388	−.039
Vocabulary	.470	−.114	.561
Similarities	.474	−.015	.466
Digit Symbol	.373	.294	.060
Picture Completion	.488	.122	.342
Spatial	.479	.559	−.103
Picture Arrangement	.487	.355	.108
Object Assembly	.572	.509	.035
Variance (%)	25.8	12.0	12.4

from +.367 to +.602, with a median of +.479. The *g* factor constitutes 25.8% of the total variance of the psychometric tests.

Table 2 also presents the loadings of each mental test on the two first-order factors. These factors reflect performance and verbal abilities and account for 12.0% and 12.4% of the variance, respectively. These findings notwithstanding, it is more important for this study that the Schmid-Leiman hierarchical factor analysis show a substantial *g* factor in the battery of psychometric tests.

A Test of the Unity of *g*

The 10 principal component scores were entered stepwise in a multiple regression analysis to predict the *g* factor scores. The specific hypothesis addressed here is not whether *any* of the principal components will add significantly to the prediction of *g*, as previous research (e.g., Vernon, 1983) suggests that this is likely, but whether *additional* components *after* the first principal component will add significantly to the prediction of *g*. If this is the case, then *g* must be the result of separate processes, as the principal components are orthogonal. Results of this analysis are presented in Table 3. This table shows that four of the first five principal components (1, 3, 4, and 5) add significant increments to the multiple R^2. The overall multiple R is .542 (R^2 = .294). The shrunken R^2, which corrects for the number of predictor variables, is .264 (R = .514). None of the other components adds significantly to the prediction of *g*.

To obtain a more accurate estimate of the multiple R in the general population, we corrected for the considerable restriction of range in this sample. The estimated restriction of range is based on the standard deviations of IQs in the

TABLE 3
Summary of the Multiple Regression of *g* Regressed on the Principal Components

Component[a]	Multiple R	R^2	F	p
1	.381	.145	19.61	.0001
3	.458	.210	8.77	.0039
4	.509	.259	4.69	.0329
5	.542	.294	6.66	.0114

[a]Component entries are cumulative.

sample in comparison to that of the general population or standardization sample. The standard deviation in this sample is ⅔ that of the standardization sample of the MAB. After the appropriate formula (McNemar, 1949, p. 126) was applied to correct for restriction of range, the multiple R of .542 was increased to .664.

To determine the effect of the components not entered in the stepwise regression, all 10 principal components were entered (forced) in a second multiple regression. The overall multiple R for this analysis is .565 (R^2 = .319), which is only slightly greater than the multiple R of .542 obtained in the stepwise regression with four components. The shrunken R^2, however, is .243 (R = .493), which accounts for 2% less variance than the stepwise multiple regression with four components as predictors.

Table 3 also shows that after the first principal component (R^2 = .145), the significant increments added to the multiple R^2 by the other principal components (viz., 3, 4, and 5) decrease markedly. Although significant, the increases in R^2 with each successive component are .065, .049, and .035. This does not, however, lessen the impact of the finding that three of the principal components, after the first, do add significant increments to the prediction of *g*.

An additional analysis was conducted to investigate the question of the statistical capitalization on chance in the multiple regression analyses or subsequent shrinkage of the multiple R in a cross-validation study. This analysis consisted of correlating the *g* factor scores with the simple unit-weighted sum of all the ECT variables (after transformation to Z scores). This correlation, which is a *lower-bound* estimate of the true correlation that an optimal combination of ECTs could have with *g*, is .439. After correction for restriction of range in the sample, this correlation increases to .558.

In order to determine the *maximum* correlation possible between the psychometric variables and the battery of ECTs, a canonical correlation was obtained among the three factor scores and the component scores on the five largest principal components of the ECTs. The canonical correlation is .603 (adjusted r = .570), which increases to .722 after correction for the restriction of range on IQ in the sample.

In hopes of identifying the latent information-processing factors in the variance of the significant components, a varimax rotation of the first five principal components (of which all except No. 2 added significantly to the multiple R) was conducted. The second principal component is included because it would change the nature of all the factors to include only the four significant components in this analysis, based on the orthogonal varimax rotation of the principal components. (The *rotated* components are hereafter referred to as *factors*.)

Table 4 shows the results of this analysis. The first two factors reflect clearly defined RT and MT factors. The remaining factors, however, are more difficult to interpret. The third factor generally has more consistently moderate loadings than the first two factors. In addition, several of the variables that load highly on this factor also tend to load relatively highly on the RT factor. The variables that load highest on this factor are the Odd-man and S–A RTMDNs and RTSDs. It may be that the (necessary) inclusion of the second principal component in this rotation has split some of the RT variance of the RT factor. The fourth factor tends to reflect a variety of variables on the MS and VS paradigms. Although the MTSD of the VS paradigm loads highly on this factor, the other variables tend to reflect the speed and efficiency of STM processing. The fifth factor is also difficult to interpret, but interesting nonetheless. The highest loadings on this factor are from IT, the only factor on which IT loads substantially, and various MTSDs. It seems that this variable may reflect individual differences in the stimulus intake speed and intraindividual variability of response execution.

The last analysis conducted was an "extension analysis" (Dwyer, 1937). This analysis was performed to ascertain the loading of psychometric g on each of the four principal components of all the ECT variables. This technique allows the determination of the loadings of g on each of the components without g itself having any effect on the factor structure determined by the ECT variables. In addition, as the psychometric g is *independently* correlated with each of the ECT components, this approach prevents the possibility of capitalization on chance (Gorsuch, 1983).

Results of the Dwyer extension analysis are shown in Table 5 (p. 410). This table displays the correlations between g and each of the ECT variables across the first five varimax factors. The loading of g on each of the four significant factors is fairly uniform (.23, .20, .23, and .31). The percent of variance explained by each of the significant components is 5.3%, 4.0%, 5.3%, and 9.6%, respectively. The total variance of psychometric g explained by these four factors is 24.2%. Because these significant factors are uncorrelated, the square root of the total variance can be used as an estimate of the multiple R. This estimate of the multiple R is .492, which increases to .615 after correction for restriction of range in the sample. In contrast to the percent of variance explained by each of the four significant factors, the percent of variance explained by the second factor is only 0.1%.

TABLE 4
Varimax Rotated Factors of the Elementary Cognitive Tasks (ECTs)[a] Based on the First Five Principal Components

ECT	Varimax Factors 1	2	3	4	5
IT	.140	.265	−.008	−.210	.486
HORTMDN	.235	.704	.027	−.075	−.067
HORTSD	.137	.560	−.144	−.128	.214
HOMTMDN	.767	.091	.119	−.098	−.222
HOMTSD	−.296	.136	−.297	.191	.330
H3RTMDN	.203	.789	.299	.016	−.115
H3RTSD	.199	.470	.215	−.094	.109
H3MTMDN	.846	..218	.040	−.029	−.141
H3MTSD	−.395	.002	−.054	−.041	.475
ODRTMDN	−.072	.570	.564	.083	−.023
ODRTSD	−.009	.245	.634	.155	.073
ODMTMDN	.886	.092	−.015	−.063	−.011
ODMTSD	−.020	−.036	−.290	.162	.583
S–DRTMDN	−.113	.656	.336	.272	−.015
S–DRTSD	−.047	.013	.206	−.064	.196
S–DMTMDN	.832	−.059	.052	.091	.124
S–DMTSD	.224	.020	−.086	.001	.132
S–ARTMDN	−.200	.557	.555	.208	−.019
S–ARTSD	.096	.080	.492	.238	.018
S–AMTMDN	.795	−.218	−.223	.168	.190
S–AMTSD	.496	−.071	−.262	.200	.208
MSRTMDN	.054	.697	.332	.399	.131
MSRTSD	.186	−.064	.329	.040	.795
MSMTMDN	.831	.259	−.070	−.035	−.021
MSMTSD	−.080	.193	.491	.217	.678
MSRTSLP	−.201	.062	.366	.541	.051
MSRTINT	.195	.749	.178	.126	.119
MSMTSLP	.196	−.177	−.458	.075	.071
MSMTINT	.817	.339	.053	−.062	−.046
VSRTMDN	.108	.715	.290	.446	.089
VSRTSD	.220	.069	−.127	.802	−.008
VSMTMDN	.852	.298	−.043	−.055	−.054
VSMTSD	−.016	.330	.082	.866	.020
VSRTSLP	−.116	.100	.380	.467	−.024
VSRTINT	.170	.754	.094	.239	.096
VSMTSLP	−.033	−.501	.314	−.164	.132
VSMTINT	.767	.401	−.204	−.030	−.108

[a]The first two letters in each variable identify the ECT paradigm, which are: Hick 0 bits (H0), Hick 3 bits (H3), Odd-man (OD), Same–Different Word Pairs (S–D), Synonym–Antonym Word Pairs (S–A), Memory Search (MS), and Visual Search (VS). The remaining (four or five) letters in each variable identify the ECT measure: Reaction time median (RTMDN), reaction time standard deviation (RTSD), movement time median (MTMDN), movement time standard deviation (MTSD), reaction time slope (RTSLP), reaction time intercept (RTINT), movement time slope (MTSLP), and movement time intercept (MTINT).

TABLE 5
Dwyer Extension Analysis Factor Loadings of *g* on the First Five Varimax Factors of the Elementary Cognitive Tasks (ECTs)

Varimax Factors				
1	2	3	4	5
.230	.034	.202	.225	.305

Note. The *g* factor loadings are reversed in sign.

DISCUSSION

Before proceeding to a discussion of the test of the main hypothesis in this study, it is important to note that, because of what can be termed "psychometric sampling error," the *g* derived from the relatively small number of mental tests ($N = 11$) in this study is not necessarily the same *g* that could be derived from a much larger sample of mental tests or from the theoretical "true" *g* of the indeterminately large population of all possible mental tests. If, however, it were assumed that this particular battery of 11 psychometric tests is a random sample of the total population of tests, then the correlation of the psychometric *g* obtained in this study with the hypothetical "true" *g* (analogous to a "true score" in classical test theory) can be estimated. The formula for this estimation, which was originally proposed by Kaiser and Caffrey (1965), is explicated in Harman (1976, p. 231). Using the eigenvalue of the first principal component of the psychometric tests in this study, the estimated correlation between the sample *g* and the "true" *g* is +.90 (i.e., the square root of the coefficient alpha in Harman's, 1976, Formula 11.29, p. 231). Therefore, to the extent that this battery of tests could be regarded as a random sample of all cognitive tests, the psychometric *g* in this study could be regarded as a valid estimate of the "true" psychometric *g*.

The *g* extracted from this battery of tests, although substantial, accounts for somewhat less of the total variance than is typically found in similar batteries. This is reflected in the moderate *g* factor loadings (.4 to .6) of many of the tests which, in many other studies, are more highly *g* loaded. For example, the APM has been found by numerous studies to be a consistently good marker test of *g*, with usual loadings on *g* in the range of .7 to .8. The APM only loads .442 on the psychometric *g* in this study.

This relatively small *g* could be due in part to the factor structure of the MAB, but it is mostly a result of university students' much more restricted range on *g* than on any of the first-order factors. This restriction of variance in *g* reflects the fact that university students are selected primarily on the basis of their SAT scores and GPAs, both of which are heavily *g* loaded. Hence, in a highly selective institution such as UC–Berkeley, the restriction of range on *g* is considerable. In this study, this is evident in the fact that the standard deviation of the full-scale IQ in the sample is only ⅔ that of the standard deviation in the standardization sample of the MAB. Another factor that probably also contributed to the rather small *g* loadings is a phenomenon, noted by Detterman and Daniel (1989), namely, that correlations among various mental tests (and hence their *g* loadings) are generally smaller in above-average IQ groups than in lower IQ groups. All of the subjects here had above-average IQs, with a mean IQ about 1.3 standard deviations above that of the general population.

In addition to restriction of range in the sample on *g*, whenever a general factor is extracted from a relatively small number of mental ability tests there is a good deal of test specificity that would usually form other first-order factors if more tests were included. The common factor variance in this battery, being based on only 11 tests, is therefore a smaller proportion of the total variance than would be the case in a much larger battery of tests, in which the common factor variance would be predictably larger than the specific variance. Nevertheless, the *g* extracted in this study is not insubstantial, constituting over one fourth of the total variance and over one half of the common factor variance.

The Unity of *g*

The main hypothesis tested in this study is whether a unitary process or a number of independent processes underlie psychometric *g*. The results of the multiple regression analysis, in which orthogonal principal components are used as the predictors of psychometric *g*, indicate that four of the first five principal components (Components 1, 3, 4, and 5) each added independent significant increments to the multiple R^2. Therefore, the underlying nature of *g* is not unitary, but must reflect at least *four independent components of variance*. The multiple *R* based on these four components is .542, which increases to .664 after correction for the considerable restriction of range in the sample on psychometric *g*. In addition, the zero-order correlation between the *g* factor scores and the simple unit-weighted sum of all the ECT variables (after transformation to *Z* scores), which was found to be .439 (.558 after correction for restriction of range), rules out the question of statistical capitalization on chance and shrinkage of the correlation in a cross-validation, as always occurs with a multiple correlation.

It is important to note that this zero-order correlation is a *lower-bound* estimate of the true correlation that an optimally weighted combination of ECTs could have with *g*. The canonical correlation shows that the *maximum* correlation possible between the psychometric variables and the battery of ECTs is .603 (adjusted $r = .570$), which increases to .722 after correction for the restriction of range on IQ in the sample. This corrected correlation is almost as high as the correlations among various standardized IQ tests, such as the Stanford-Binet and the Wechsler scales (Jensen, 1980, p. 315).

Moreover, if the heritability of psychometric *g*, which is estimated to be about .70 (Plomin, DeFries, & McClearn, 1990), largely reflects the "hardware" or biological component of variance in *g*, then the correlation between individual differences in the actually measured, or *phenotypic*, *g* and the corresponding *genotypic* values would be the square root of .70, or about .84. So, if in the general population the correlation between this battery of ECTs and *g* is estimated at about .70, as previously indicated, it could be said to reflect about 70% of the genotypic variance in *g* (i.e., 100 $(.70/.84)^2$).

In sum, the results do not support the theory that a unitary process underlies psychometric *g*. Rather, they support Detterman's (1987) theory that various mental tests correlate highly with each other because each of them draws upon many of the same elemental processes. This theory also explains the quite moderate correlations between the various ECTs and *g*. Each ECT accounts for only a small fraction, but a partially independent fraction, of the variance in *g*. Further research is needed to determine the precise number and nature of these components. As Jensen (1987c) noted, however, the fact that individual differences in *conceptually distinct processes* (as measured by ECTs) are correlated indicates the presence of some more fundamental level of processes, presumably neurological, which are shared by conceptually distinct information processes.

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APPENDIX

TABLE A–1
Descriptive Statistics for the Psychometric Tests

Mental Test	*M*	*SD*	*T*	*SD*
MAB Verbal Scale				
Information	27.32	6.10	54.78	7.52
Comprehension	22.57	2.46	55.60	4.23
Arithmetic	15.61	2.69	59.84	8.08
Similarities	27.97	3.40	59.97	4.58
Vocabulary	32.52	7.52	60.39	7.96
MAB Performance Scale				
Digit Symbol	27.37	3.61	62.47	8.11
Picture Completion	23.61	3.99	51.83	6.39
Spatial	32.59	7.88	57.77	9.20
Picture Arrangement	13.24	1.91	60.62	7.82
Object Assembly	14.85	3.43	57.68	6.93
MAB Verbal IQ[a]	125.99	17.00	119.28	9.88
MAP Performance IQ	111.66	15.20	117.96	12.24
MAB Full Scale IQ	237.65	27.46	120.17	10.88
Raven's APM[b]	26.91	5.61	117.54	9.97

[a]$M = 100$, $SD = 15$. [b]$M = 100$, $SD = 16$.

TABLE A–2
Descriptive Statistics (in ms) for the Hick and Odd-man Paradigms

	Median		Intraindividual *SD*		
Paradigm	**RT**	**MT**	**RT**	**MT**	**No. of Errors**
Hick 0 Bits					
M	275.59	171.52	32.86	115.88	0.73[a]
SD	30.43	46.55	15.20	91.98	1.61
Hick 3 Bits					
M	331.88	182.82	36.97	117.52	0.11
SD	36.40	50.41	11.43	60.96	0.24
Odd-man					
M	484.55	207.94	95.36	155.63	0.76
SD	76.85	68.42	52.47	72.66	1.02

[a]Based on $N = 98$.

TABLE A–3
Descriptive Statistics (in ms) for the Posner Paradigm

	Median		Intraindividual *SD*		
Paradigm	**RT**	**MT**	**RT**	**MT**	**No. of Errors**
Same–Different					
M	683.07	145.26	229.89	122.30	2.20
SD	144.45	71.71	233.94	190.01	1.55
Synonyms–Antonyms					
M	915.50	177.71	230.69	145.38	3.79
SD	196.51	101.53	138.05	91.08	2.48

TABLE A–4
Descriptive Statistics (in ms) for the Memory Search (MS) and Visual Search (VS) Paradigms

	Median		Intraindividual *SD*		
Paradigm	**RT**	**MT**	**RT**	**MT**	**No. of Errors**
Memory Search					
M	537.64	121.05	173.17	466.96	3.68
SD	93.55	51.27	172.95	167.72	2.23
Visual Search					
M	568.54	117.75	200.28	519.59	3.60
SD	98.12	46.01	80.37	175.77	2.34

	Slope		Intercept	
Paradigm	**RT**	**MT**	**RT**	**MT**
Memory Search				
M	24.64	1.96	441.27	114.97
SD	13.02	4.21	79.65	48.73
Visual Search				
M	23.89	−0.15	484.16	119.1
SD	14.66	4.06	87.72	53.38

TABLE A–5
Descriptive Statistics for the Inspection Time (IT) Paradigm

Variable	***M***	***SD***
Inspection Time	45.36 ms	20.24 ms
Trials	119.02	31.30
Errors	20.12	7.21
Decision Time		
Error-free Trials	687.44 ms	279.11 ms
Error Trials	954.96 ms	468.37 ms

TABLE A–6

Elementary Cognitive Task (ECT)[a] Intercorrelations[b]

		Hick 0-Bit Condition				Hick 3-Bit Condition			
	IT	RTMDN	RTSD	MTMDN	MTSD	RTMDN	RTSD	MTMDN	MTSD
IT									
H0RTMDN	210								
H0RTSD	212	402							
H0MTMDN	−018	245	152						
H0MTSD	−034	−108	105	−190					
H3RTMDN	216	760	372	239	−078				
H3RTSD	246	269	397	203	074	478			
H3MTMDN	084	408	207	797	−238	385	268		
H3MTSD	004	−094	014	−381	188	−205	−062	−316	
ODRTMDN	186	448	158	−029	−051	664	399	077	−003
ODRTSD	194	213	−031	067	042	340	248	068	−011
ODMTMDN	152	317	205	758	−255	259	242	903	−348
ODMTSD	247	−067	060	−132	311	−139	107	−057	316
S–DRTMDN	102	335	243	029	001	525	284	037	071
S–DRTSD	094	−057	045	−104	−092	031	−018	−057	186
S–DMTMDN	133	108	143	570	−235	107	154	635	−248
S–DMTSD	055	061	−044	089	003	070	−001	191	−053
S–ARTMDN	023	244	160	−041	073	528	375	−010	071
S–ARTSD	−005	114	−054	054	−033	248	259	032	016
S–AMTMDN	103	073	040	423	−129	−051	−010	510	−274
S–AMTSD	117	102	032	183	113	−063	−095	279	−088
MSRTMDN	091	423	292	073	073	606	306	166	−031
MSRTSD	286	−014	097	023	115	009	068	051	241
MSMTMDN	145	288	213	606	−161	307	299	694	−251
MSMTSD	217	091	151	−112	166	215	111	−091	196

(continued)

TABLE A–6
(Continued)

		Hick 0-Bit Condition				Hick 3-Bit Condition			
	IT	RTMDN	RTSD	MTMDN	MTSD	RTMDN	RTSD	MTMDN	MTSD
VSRTMDN	123	437	289	115	055	608	311	191	−014
VSRTSD	−017	098	107	072	097	138	097	218	−143
VSMTMDN	180	350	289	656	−164	384	292	751	−302
VSMTSD	−005	203	144	−061	140	324	142	064	−046
MSRTSLP	−060	−004	−082	−167	120	172	104	−124	085
MSRTINT	134	486	375	202	−001	590	271	279	−094
MSMTSLP	096	−113	−110	158	−007	−244	−050	044	008
MSMTINT	125	350	249	638	−169	399	334	719	−272
VSRTSLP	−088	−005	009	−032	−011	152	005	−080	058
VSRTINT	191	505	322	147	072	598	319	249	−044
VSMTSLP	−076	−298	−083	−091	−096	−272	−025	−173	044
VSMTINT	168	404	296	589	−123	408	251	713	−279

	Odd-man				Same–Different			
	RTMDN	RTSD	MTMDN	MTSD	RTMDN	RTSD	MTMDN	MTSD
ODRTMDN								
ODRTSD	665							
ODMTMDN	−047	−024						
ODMTSD	103	−035	054					
S–DRTMDN	466	302	−077	−104				
S–DRTSD	056	030	−043	−051	191			
S–DMTMDN	−047	051	717	042	−105	−005		
S–DMTSD	010	038	140	049	000	106	146	
S–ARTMDN	568	446	−120	−011	689	131	−189	−148
S–ARTSD	314	367	027	−048	194	091	077	−018

S–AMTSD	−150	−128	337	172	−046	−078	391	177
MSRTMDN	558	348	078	−030	621	069	051	014
MSRTSD	056	172	140	211	037	105	216	045
MSMTMDN	063	005	685	018	045	−023	584	154
MSMTSD	305	327	−062	114	325	130	032	003
VSRTMDN	562	406	112	−031	721	058	196	025
VSRTSD	081	110	166	158	143	−043	205	049
VSMTMDN	055	−001	735	−088	113	−052	655	150
VSMTSD	333	297	024	091	456	011	062	000
MSRTSLP	274	332	−157	029	286	049	−117	−090
MSRTINT	468	221	193	−061	553	057	134	099
MSMTSLP	−315	−304	174	172	−315	−050	066	017
MSMTINT	164	010	676	−027	145	−023	592	157
VSRTSLP	285	170	−144	018	431	044	−077	−152
VSRTINT	470	357	192	−053	574	030	237	108
VSMTSLP	−105	−038	−101	048	−216	045	−022	−041
VSMTINT	019	−083	664	−106	135	−063	549	107

	Visual Search				Memory Search			
	RTMDN	RTSD	MTMDN	MTSD	RTSLP	RTINT	MTSLP	MTINT
S–ARTMDN								
S–ARTSD	454							
S–AMTMDN	−445	057						
S–AMTSD	−280	064	639					
MSRTMDN	647	260	−106	026				
MSRTSD	066	103	201	104	195			
MSMTMDN	024	064	539	375	236	089		
MSMTSD	367	199	−062	−058	550	852	−136	
VSRTMDN	606	282	−005	090	763	149	223	413

(*continued*)

TABLE A–6
(Continued)

	Synonym–Antonym				Memory Search			
	RTMDN	RTSD	MTMDN	MTSD	RTMDN	RTSD	MTMDN	MTSD
VSRTSD	052	154	294	136	238	039	141	087
VSMTMDN	014	055	545	313	201	102	839	−083
VSMTSD	353	247	057	030	519	059	−020	295
MSRTSLP	442	164	−255	−152	473	130	−126	361
MSRTINT	466	191	040	133	844	159	343	422
MSMTSLP	−234	−069	224	205	−148	−052	312	−258
MSMTINT	086	080	504	350	305	102	953	−067
VSRTSLP	380	156	−175	010	402	096	−034	290
VSRTINT	451	205	080	094	630	092	255	285
VSMTSLP	−086	041	053	−068	−308	122	−137	005
VSMTINT	000	041	481	328	213	034	805	−130

	Visual Search				Memory Search			
	RTMDN	RTSD	MTMDN	MTSD	RTSLP	RTINT	MTSLP	MTINT
VSRTMDN								
VSRTSD	259							
VSMTMDN	251	185						
VSMTSD	630	859	007					
MSRTSLP	291	284	−132	416				
MSRTINT	693	100	315	338	−062			
MSMTSLP	−203	058	170	−116	018	−202		
MSMTINT	302	124	836	008	−141	438	025	
VSRTSLP	444	152	−082	387	357	242	−175	009
VSRTINT	865	202	323	490	125	643	−125	320
VSMTSLP	−311	−119	−129	−194	−038	−327	−028	−160
VSMTINT	262	196	913	035	−179	350	212	788

	Visual Search			
	RTSLP	RTINT	MTSLP	MTINT
VSRTSLP				
VSRTINT	−053			
VSMTSLP	−039	−339		
VSMTINT	−089	343	−386	

[a]The first two letters in each variable identify the ECT paradigm, which are: Hick 0 bits (H0), Hick 3 bits (H3), Odd-man (OD), Same–Different Word Pairs (S–D), Synonym–Antonym Word Pairs (S–A), Memory Search (MS), and Visual Search (VS). The remaining (four or five) letters in each variable identify the ECT measure: Reaction time median (RTMDN), reaction time standard deviation (RTSD), movement time median (MTMDN), movement time standard deviation (MTSD), reaction time slope (RTSLP), reaction time intercept (RTINT), movement time slope (MTSLP), and movement time intercept (MTINT).

[b]Decimals are omitted in the component loadings.

TABLE A–7

Intercorrelations Among the Psychometric Variables

	APM	**Info**	**Arith**	**Comp**	**Vocab**	**Sim**	**Digit**	**Pcomp**	**Spatial**	**PArrange**	**ObjAsm**
APM	1										
Info	.185	1									
Arith	.226	.566	1								
Comp	.465	.247	.220	1							
Vocab	.129	.524	.463	.082	1						
Sim	.143	.566	.562	.256	.536	1					
Digit	.250	.342	.169	.283	.236	.128	1				
PComp	.298	.479	.513	.036	.367	.338	.233	1			
Spatial	.435	.329	.111	.372	.217	.043	.386	.273	1		
PArrange	.309	.346	.247	.263	.348	.199	.281	.367	.504	1	
ObjAsm	.561	.375	.267	.361	.240	.216	.342	.447	.507	.501	1

Note. Psychometric test names, in order, are: Raven's Advanced Progressive Matrices, Information, Arithmetic, Comprehension, Vocabulary, Similarities, Digit Symbol, Picture Completion, Spatial, Picture Arrangement, and Object Assembly.