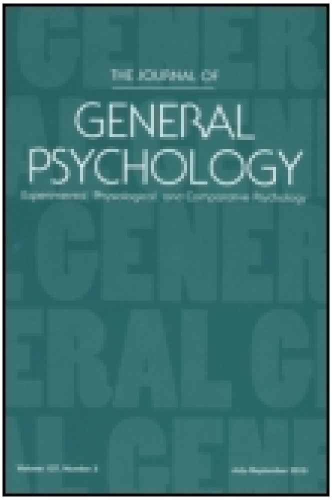

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Individual Differences in Performance on Elementary Cognitive Tasks (ECTs): Lawful vs. Problematic Parameters

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Individual Differences in Performance on Elementary Cognitive Tasks (ECTs): Lawful vs. Problematic Parameters

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ABSTRACT. Over the past 2 decades, the cognitive-correlates approach has dominated investigations into the nature of intelligence. This research program relies on a number of processing speed parameters (apart from "average performance"). These measures include the slope, intercept, and intraindividual variability of both *decision time* and *movement time*. By correlating these measures with established markers of intelligence, researchers postulate theoretical models underlying these information-processing constructs. However, there is a lack of substantive evidence that these phenomena are as robust within the individual as has been proposed. The authors tested the properties of intraindividual parameters by asking participants ($N = 179$) to perform 10 elementary cognitive tasks (ECTs). Detailed analyses revealed that average performance parameters, extracted from these ECTs, behaved lawfully. However, up to 40% of participants failed to provide acceptable indices of intraindividual model fit. Similarly, intraindividual variability measures appeared less valid than previously suggested. The implications of these findings for cognitive and biological models of intelligence are discussed.

Key words: cognitive abilities, elementary cognitive tasks, reaction time, speed of processing

THE PROMINENT individual-differences psychologist John B. Carroll (1995) suggests that the goal of intelligence research is to explore "the *diversity of intellect* in the people of this planet—the many forms of cognitive processes and operations, mental performances, and creations of knowledge and art" (p. 429). However, for the past 20 years, many investigators have focused on a single aspect of this entreaty—the search for a basic operation underlying intelligence. Much of that work has focused on the role of the speed of mental processing (see Stankov & Roberts, 1997, for a critical review). Indeed, Hunt (1999) considered that "information-processing models are essential to relate neuroscience observations to behavior" (p. 7). Nonetheless, certain aspects of this research program do not always appear to be treated with the rigor demanded by the scientific approach (Mackintosh, 1998). In this article we present a critical appraisal of the methodology adopted to understand an influential construct in the study of intelligence: processing (or mental) speed.

The study of intelligence (or more formally, human cognitive abilities) has been dominated largely by the cognitive-correlates approach (which makes use of information-processing constructs, particularly those measured by performance speed) since the late 1970s. The investigation of factorially simple tasks, which are not especially cognitively demanding, has prompted hopes of arriving at a definition of intelligence that is both precise and explanatory (Hunt, 1978). This approach is guided in task selection by theory-based experimental paradigms originating from within cognitive psychology. Parameters derived from a range of elementary cognitive tasks (ECTs) are selected and, on the basis of existing substantive theory, relations between information-processing and intelligence constructs are predicted (Brody, 1992; Carroll, 1981, 1993).

The types of experimental tasks employed under this research program have been both diverse and numerous. Among the more frequently employed ECTs are Saul Sternberg's (1969) memory search paradigm, Shepard and Metzler's (1971) mental rotations task, the Posner paradigm (e.g., Posner, 1978), and Clark and Chase's (1972) sentence verification task (e.g., Hunt, Davidson, & Lansman, 1981). For the benefit of those readers unfamiliar with these measures, and to emphasize the hypothesized "elementary" nature of these ECTs, examples of such paradigms are presented in Figure 1. In each instance, speed of response is the performance measure of interest, because error rates tend to be low and randomly distributed across individuals.

In many instances, postulated relationships between information-processing and intelligence constructs have been manifest. It remains unclear, however, whether sufficient attention has been afforded to the range and type of psychometric tests with which measures derived from these ECTs are correlated (Carroll, 1993, p. 647*ff.*; Juhel, 1991). Despite this criticism, perhaps the most widely adopted "family" of ECTs within intelligence research uses principles derived

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You have five seconds to examine and remember the following sequence of letters:

1a X - R - T - B - Z

Was the following letter amongst the sequence?

F

Look at the two letters below.
1b Are they the same or different?
Respond as quickly as possible.

Examples of different conditions:

A - A
A - b
a - A
a - a
and so on

Answer: YES / NO

Is the following sentence correct in the picture that follows?

1c STAR IS BELOW CROSS

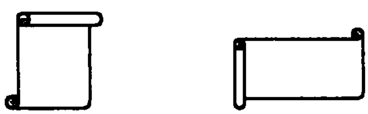
*

X

Answer: YES / NO

Can the shape on the left be rotated to be the shape as that on the right?

1d



Answer: YES / NO

FIGURE 1. Examples of ECTs used in the cognitive-correlates approach by intelligence researchers. FIGURE 1a. Saul Sternberg's (1969) short-term memory task. FIGURE 1b. Posner's (Posner & Mitchell, 1967) letter-comparison task. FIGURE 1c. Clarke and Chase's (1972) sentence verification task. FIGURE 1d. Shepard and Metzler's (1971) mental rotations task.

from information theory (e.g., Anderson, Nettelbeck, & Barlow, 1997; Bates & Stough, 1997; Beauducel & Brocke, 1993; Kranzler, 1994; Lindley, Wilson, Smith, & Bathurst, 1995; Neubauer & Knorr, 1997). It is to a brief exposition of this approach that we now turn.

In general, two dependent variables are recorded from ECTs subscribing to the information-theory model. These variables are *movement time* (MT), the speed associated with sensory and motor control of movement, and *decision time* (DT), the time required to determine and initiate an appropriate response to stimuli. A number of trials and treatment conditions are also employed, making it practical (and theoretically defensible) to derive additional parameters. For instance, in the Hick paradigm, the number of elements in the array from which the participant is required to respond is increased. Because it is an established empirical phenomenon that DT increases linearly with a logarithmic transformation of the number of stimulus alternatives, this allows functions to be fit to the underlying experimental manipulation. Table 1 lists the most frequently investigated parameters derived under the information-theory framework. Table 1 also includes a proposed, standard nomenclature for each performance parameter employed in the extant literature.[1]

Of critical importance is that each of the so-called intraindividual parameters listed in Table 1 is assumed to represent basic processes of the human cognitive system. For example, the slope of DT is hypothesized to reflect the rate at which information is stored and processed (Roth, 1964). Measures of intraindividual variability, on the other hand, are assumed to reflect consistency of response (Jensen, 1992). It also transpires that almost all of these parameters are reported to exhibit moderate correlation with measures of intelligence (i.e., *r*s in excess of –0.30 in magnitude; e.g., Jensen, 1987). Based on such empirical demonstrations, a variety of explanatory models have been postulated (see Stankov & Roberts, 1997, for a critical review). Those models include theories that stress the importance of neural noise, errors in neural transmission, degree of myelination, neural efficiency, nerve conduction velocity, lapses in attention, working memory capacity, and so forth (e.g., Bates & Stough, 1997, 1998; Jensen, 1993, 1998; Larson & Alderton, 1990; Lindley et al., 1995; Miller, 1994).

Rationale and Main Aims of the Study

Among researchers examining intelligence from the perspective of cognitive psychology, there is seemingly a consensus that findings obtained with ECTs have both empirical and conceptual significance. Furthermore, this notion is not simply restricted to paradigms subscribing to information theory but to all such

[1]Early attempts to model ECTs used global measures of *reaction time* (RT). It is now commonplace to find the many parameters of DT and MT listed in Table 1 being assessed in almost all ECTs (see Carroll, 1993, p. 478*ff*.).

instances where cognitive models have been applied to the investigation of individual differences.

In opposition to what virtually amounts to a Zeitgeist, some researchers have argued that there are intrinsic problems in the assumptions underlying the extraction of many cognitive parameters stemming from ECTs (e.g., Ippel, 1986; Lohman, 1994, 1999). Indeed, empirical examination of the measures listed in Table 1 seems to have received less attention than this important conceptual issue warrants. With intraindividual parameters, frequently three (and at most four) data points have been used to derive a subset of measures (e.g., the slope constant). Interestingly, those parameters have not been subjected to the same degree of rigorous statistical analysis as that given to generic measures of central tendency. Because only a single, isolated ECT is frequently employed in cognitive-correlates research, there has also been little attempt to determine whether any processing speed parameter has construct validity. For example, slope DTs from various ECTs should share moderate-to-high correlation with one another if, as suggested, the measure assesses a meaningful psychological construct (i.e., rate of information processing). The undertaking of an examination of these parameters gains considerable impetus from Carroll's (1993) assertion that "it is not possible . . . to derive clear evidence for a definite set of speed factors in ECTs" (p. 484).

Thus, the main aim of the current study was to critically evaluate the empirical status of each of the intraindividual parameters given in Table 1. In so doing, the investigation addresses the construct validity of those processing parameters that have led to models of human intelligence. To this end, ECTs containing up to eight treatment conditions (compared to the more common three or four) were employed within the framework of a multivariate design. Measures were analyzed both within single ECTs and across a battery of such tasks. The literature presents considerable information on methods of establishing the validity of the processing speed parameters that are listed in Table 1. Those methods include application of a variety of regression and correlational procedures to assess model appropriateness. Consequently, where possible, each performance measure was subject to the same degree of statistical scrutiny.

Task Selection and Its Implications Beyond the Present Design

In order to adhere to the stated principles of the cognitive-correlates approach, each ECT was carefully chosen for the present investigation on the basis of existing psychological theory. Thus, each ECT was selected on the proviso that there had been previous empirical research linking its parameters with measures of intelligence. Furthermore, a given cognitive model had to have been postulated in order to account for this relationship. For example, a theory indicating the centrality of both cognitive complexity and attentional mechanisms has been derived to account for dual (or competing) task manipulations of speed of information-processing measures. That theory also happens to account for the fact that this type of ECT

TABLE 1
Frequently Measured Individual Differences Parameters of ECTs

Variable	Description	Symbol	ECTs
Median DT	Median DT over all trials for a given number of bits	DT_0, DT_1, etc.	3–10
Mean median DT	Mean of the median DT over bits	DT_X	3–10
Intraindividual variability in DT	The average standard deviation of DT over trials at each number of bits	$sdDT_0$, $sdDT_1$, etc.	3, 5, 6
Mean intraindividual variability in DT	The mean of the average standard deviation of DT obtained at each number of bits	$sdDT_X$	3, 5, 6
Median MT	Median MT over all trials for a given number of bits	MT_0, MT_1, etc.	1, 3–10
Mean median MT	Mean of the median MT over bits	MT_X	1, 3–10
Intraindividual variability in MT	The average standard deviation of MT at each number of bits	$sdMT_0$, $sdMT_1$, etc.	3, 5, 6
Mean intraindividual variability in MT	The mean of the average standard deviation of MT obtained at each number of bits	$sdMT_X$	3, 5, 6
Intercept of MT	Intercept of the regression of mean MTs on bits	MTa	1
Slope of MT	Slope of the regression of mean MT on bits	MTb	1
Fit of MT	Index of fit determined from the regression of MT on bits (Pearson product-moment coefficient)	MTr	1
Median RT	(Median DT + Median MT) over all trials for a given number of bits	RT_0, RT_1, etc.	2–10
Mean median RT	Mean of the median RTs (as above) obtained at each number of bits	RT_X	2–10
Intraindividual variability in RT	Average standard deviation of the RTs (i.e., sdDT + sdMT) at each number of bits	$sdRT_0$, $sdRT_1$, etc.	2

(table continues)

TABLE 1 (continued)
Frequently Measured Individual Differences Parameters of ECTs

Variable	Description	Symbol	ECTs
Mean intraindividual variability	The mean of the average standard deviation of RTs obtained at each number of bits	$sdRT_X$	2
Intercept of RT	Intercept of the regression of median RTs on bits	RTa	2–5, 7–10
Slope of RT	Slope of the regression of median RTs on bits	RTb	2–5, 7–10
Fit of RT	Index of fit determined from the regression of RT on bits (Pearson product-moment coefficient)	RTr	2–5, 7–10

Note. ECT = elementary cognitive task. DT = decision time. MT = movement time. RT = reaction time. See also "Individual Differences in the Hick Paradigm," by A. R. Jensen, 1987. In P. A. Vernon (Ed.), *Speed of Information-Processing and Intelligence* (pp. 101–175). Norwood, NJ: Ablex.

shares moderate-to-high correlation with indices of general intelligence (Brody, 1992, p. 97*ff.*; Roberts, Beh, Spilsbury, & Stankov, 1991; Roberts, Beh, & Stankov, 1988). Provided that an ECT satisfied these important prerequisites, it remained a candidate for the present multivariate design.

It is important to reiterate that contemporary intelligence theories usually assume that a given processing parameter is representative of a basic property of the human information-processing system (Brody, 1992). From such a perspective it might be argued, somewhat paradoxically, that the particular ECT by which performance is assessed (e.g., the sentence-verification task as opposed to any of those described later in the Method section) is largely incidental (Stankov & Roberts, 1997).[2] This follows from the fact that the information-processing paradigms employed are generally assumed to be representative of the more global construct of cognitive (or mental) speed (e.g., Hale & Jansen, 1994; Neubauer & Bucik, 1996; Salthouse, 1996). Nevertheless, because of the stated aims of the present study, which imply the need to extract comparable parameters across ECTs, it was deemed necessary that each condition could be measured using analogous conceptual principles. Information theory provided a standard procedure for attaining this goal (see Shannon & Weaver, 1949). Task selection was thus also directed toward meeting this requirement.

[2]It is important to point out that not all researchers take this view (e.g., Hunt, 1978) although it is becoming more and more commonplace.

The data that were collected with this battery of ECTs are also valuable for studying the factorial structure of cognitive speed constructs. Elsewhere, Carroll (1993) has suggested that cognitive speed measures may form an important part of a comprehensive (taxonomic) model of human cognitive abilities. "If any broad taxonomic model of cognitive ability factors were to be formulated, in fact, it might be one based on the distinction between level and speed" (Carroll, 1993, p. 644). Even so, information on individual differences in speed-related behavior is currently meager, essentially because of problems implicit in previous research designs (Carroll, 1993, p. 484). The present paper does not explicitly address the factorial structure of the ECTs that were employed. However, it is an important companion to several articles that do, because it suggests the most efficacious performance parameters to enter into hierarchical factor analyses (see Roberts, Pallier, & Goff, 1999; Roberts & Stankov, 1999).

Projected Data Analyses

A variety of findings reported in the experimental literature on reaction time (RT), and more recent studies examining individual differences in processing speed, suggested the type of statistical tests to which each of the parameters should be subjected. In addition, because of an interest in determining the conceptual status of each psychological construct, further forms of analyses were apparent. The five major analytical principles by which each of the parameters of the ECTs would be systematically evaluated are given below.

Assessment of model appropriateness via trend and/or regression analyses. It was postulated, a priori, that the majority of ECTs would subscribe to the Hick-Hyman law: $RT = a + b \log_2 [n]$ (e.g., Hick, 1952; Hyman, 1953). Consequently, these analyses would appear critical in establishing the validity of median performance parameters. It has also been demonstrated that measures of intraindividual variability share a linear relationship with set size (i.e., n; see Jensen, 1987). In a fashion similar to measures of central tendency, this relationship should manifest itself across many of the ECTs in the present study. With respect to intraindividual regression parameters, it would seem necessary to ascertain whether the majority of participants complied with the underlying model. In short, the percentage of individuals providing acceptable (and unacceptable) indices of model fit was assessed (e.g., Barrett, Eysenck, & Lucking, 1986).

Confirmation (or otherwise) of a simplex pattern of intercorrelations within the conditions of an ECT. Simplex is a pattern of correlations where values close to the main diagonal are large and taper off toward the left-hand corner of a correlational matrix (Guttman, 1955). It is claimed that simplex is a natural consequence of two features of processing speed data: the increase in response time as a function of task difficulty and the relative independence of individual differences in the slope and intercept of the linear model describing this empirical relationship (Jensen, 1987). The presence of simplex would seem a pivotal corollary of theories stressing the importance of complexity of processing (Roberts et al., 1988).

Correlational analysis between the different ECTs employed in the study. Demonstration of consistently low correlation on a given measure (e.g., slope RT) across the battery of ECTs would indicate that a certain parameter lacks construct validity. Equally, demonstration of moderate-to-high correlation between ECTs would indicate that a particular parameter is construct valid. This is an important point because the vast majority of theoretical models cited in the introduction of this article (i.e., theories based on neural transmission rate, errors in neural transmission, degree of myelination, etc.) predict this latter result on a priori grounds.[3]

Examination of the pattern and magnitude of correlation coefficients found between parameters of the same ECT. Consistently high correlation between two measures (e.g., intercept DT, median DT) would indicate redundancy in either or (in the case of a third variable also sharing high correlation) both parameters (see, e.g., Jensen, 1987). Under certain circumstances, such a finding might be taken to question the empirical efficacy of a given parameter, particularly if one parameter is shown to be construct valid and another less so. In such instances, the valid measure should clearly be used to derive the underlying conceptual model—a point that is obviously consequential to theory construction.

Assessment of the reliability of each ECT employed in the study. Adequate reliability is required in a psychological measure if it is to be used to generate a theoretically meaningful model—a point not always acknowledged in the cognitive-correlates approach to intelligence.

Summary

Briefly, the main aim of the study was to elucidate the appropriateness of some of the main assumptions underlying the cognitive-correlates approach to the study of human cognitive abilities. In particular, the psychometric properties of various parameters derived from this approach, and the nature of assumed relationships between typical ECTs used in research studies, were investigated. To this end, 10 tasks that were deemed to meet the criteria outlined previously, and that were amenable to greater experimental manipulation than has been usual, were selected. The tasks chosen are described in detail in the passages that follow.

[3]This is a logical consequence of the reductionist framework under which such models are generally formulated (see Brody, 1992, Chapter 3 ["*g* and Basic Information-Processing Skills: The Search for the Holy Grail"]).

Method

Participants

One hundred seventy-nine (179) participants were involved in the study. The majority of these participants (82%) were first-year psychology students at the University of Sydney who participated in order to fulfill course requirements. The remainder of the sample was drawn from adult education classes in western Sydney. Those participants engaged in the study out of a professed interest in assisting this research initiative. The age of participants ranged from 17 to 50 years with a mean of 21.58 years ($SD = 6.18$ years). One hundred ten of the participants were female. It should be noted that the population drawn from outside the university was particularly well educated, holding bachelor's degrees (or higher).[4]

Experimental Measures

All participants completed 10 ECTs. In all such instances, the length of practice and number of experimental trials given resembled that reported in the intelligence literature.[5] For each of these tasks, the dependent variable was time-per-response measured in milliseconds. All paradigms involved manipulations of task difficulty that could be scaled into bits using principles derived from information theory. The parameters obtained from each task are given in Table 1. For the frequently used ECTs, the standard procedures were implemented, and the original sources can be consulted for comparison purposes.

Test 1: Fitts' Movement Task. In this task, participants were required to tap a small metal probe between two targets as quickly and accurately as possible. Task difficulty was manipulated by varying target width (Fitts, 1954). With the formula underlying Fitts' law, values of task difficulty were subsequently scaled into information units (see Roberts, 1997b; Welford, 1968). Five conditions were selected for investigation: 2.88, 3.34, 4.05, 4.62, and 5.66 bits. The dependent variable throughout the five conditions was the number of cycles made in 60 s. In order to make it comparable to previous studies and other parameters examined in the investigation, we subsequently transformed this measure into a rate measure.

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[4]As a test of the equivalence between the two groups comprising the sample, partial correlations (with age controlled) were employed in several reanalyses of the ECTs. In addition, parameters listed in Table 1 were examined only for the University sample. Results were, without exception, comparable to those reported for the entire sample.

[5]As such, the number of practice trials ranged between 5 and 20 trials per paradigm, with the number of experimental trials per condition varying anywhere between 1 (for more "global" measures) and 20. For further details, the reader is referred to the comprehensive Web site given later in this article (see also Roberts, 2000).

Test 2: Joystick Reaction Task. In this task, participants were presented with a central fixation point on the computer screen in addition to varying numbers of lines emanating from this point at 45° increments from the horizontal (see also Fitts & Seeger, 1953). The number of lines ranged from 1 to 8 (inclusive). At the end of each line was a small open circle of 0.5-cm diameter. The participants' task was to move a hand-held joystick from its resting position—a point corresponding to the central fixation point—in the direction of a circle that became illuminated (after a variable fore-period). RT was determined from initiation of the signal to termination of the response by the participant's movement of the joystick.

Test 3: Single Response Choice Reaction Task. This task was akin in design and format to the choice RT paradigm that has been employed most extensively to examine the relationship between speed of processing, stimulus information, and intelligence (e.g., Jensen, 1982, 1987). The set sizes manipulated were 1, 2, 4, 6, and 8 *n*. Because the design of Test 3 employed a home key, both MT and DT were independently assessed (to the nearest millisecond).

Test 4: Tachistoscopic Choice Reaction Task. In this paradigm, 2, 4, or 8 parallel lines were exposed to each participant for periods ranging between 40 and 480 milliseconds (in equal increments of 40 ms). An 8-cm line at the bottom joined the lines. Within any trial condition, a single line was smaller by 2% than the other stimuli, which were 8-cm high. In all, there were 360 trials covering each cross of task difficulty and exposure duration. Each participant was required to lift his or her finger from a home button and move it to a response key indicating the serial position of the perceived shortest line. Note that there is rather extensive empirical literature dealing with the effects of exposure duration on RT (e.g., Christ, 1970; Kaswan & Young, 1965).[6]

Test 5: Complex Choice Reaction Task. In this task, the stimuli, method of presentation, and mode of response were analogous to that employed in the Single Response Choice Reaction Task. However, a simple procedural difference was introduced. Instead of one stimulus target becoming illuminated, several did so simultaneously. The participants' task was to press each number key corresponding to filled-in targets. The number of targets employed was 2 for set sizes of 4, 6, and 8; 3 for set sizes of 6 and 8; and 4 for an array size of 8. By implementing a mathematical extension of the Hick-Hyman law, it was possible to determine

[6]The reader may note similarities between this ECT and tasks falling under the *inspection time* (IT) paradigm. Although there are some points of methodological overlap, the present task differs from recent studies of IT in that (a) neither a forward nor a backward mask was employed; (b) conditions extending beyond a simple binary decision were included; and (c) both MT and DT were recorded in addition to the conventional measure of accuracy (see Deary & Stough, 1996; Kranzler & Jensen, 1989; Nettelbeck, 1987).

stimulus values (Beh, Roberts, & Prichard-Levy, 1994). These information levels ranged from 2.58 to 6.12 bits—stimulus values that extend beyond those typically investigated in RT tasks. Note that in its previous application, parameters derived from this ECT were found not only to subscribe to information-theory principles but also to share higher correlation with psychometric measures than those traditionally assessed in the Hick paradigm (Beh et al., 1994).

Test 6: Binary Reaction Task. This task incorporated methodological aspects from both Test 3 and Test 5. Participants were given a simple rule requiring a binary decision and response. For example: If the number 8 light becomes illuminated press "Yes"; otherwise press the "No" key. Note that this task parallels the widely employed "odd-man-out" paradigm (e.g., Frearson, Barrett, & Eysenck, 1988; Frearson & Eysenck, 1986; see Roberts, 2000, for a detailed comparison) and that this type of task generally shares higher correlation with psychometric measures than that found with more "traditional" choice reaction paradigms (Diascro & Brody, 1994).

Test 7: Single Card-Sorting Task. This task used the informational properties of a simple deck of playing cards (see Crossman, 1953). In it, participants were required to perform four subtasks in various random orders. The conditions included sorting into alternate piles without consideration of any physical characteristics of the cards (0 bits), sorting according to the color of the cards (1 bit), sorting into suits (2 bits), and sorting according to number and suit (3 bits). Following the rationale outlined in Roberts et al. (1991), this task (as well as Tests 8–10) was administered within a 60-s time interval. This variable was subsequently transformed into a speed measure (scaled in milliseconds) in order to make it comparable to the other chronometric variables of the current investigation. In order to obtain some indication of reliability over the four conditions, we administered each subtask on three separate occasions (corresponding to the three different experimental manipulations underlying Test 8).

Test 8: Multitask Card Sorting. Three tasks collectively defined this paradigm's structure. Each involved instructions emphasizing different attentional requirements for simultaneous presentation of two information theory tasks: the card-sorting paradigm described previously and word-classification tasks to be described shortly (see also Roberts et al., 1988, 1991).

In the first of these ECTs—the competing task condition—participants were required to divide their attention equally between the two tasks. In a second version, participants were required to attend principally to the cards. In a third and final version, participants were directed to focus attention mainly upon the words (Stankov, 1987, 1989). Each participant performed 16 subtasks (representing the cross of the four levels of the card-sorting paradigm and four levels of the word-classification task) under each of these experimental manipulations.

Test 9: Single Word-Classification. Four conditions were constructed for this task, corresponding to 0, 1, 2, and 3 bits of stimulus information. Each of these consisted of a list of 32 words defined by prearranged categories (e.g., sport, weapon, fruit, or vehicle), which the experimenter read aloud. The participants were required to state (orally) the category to which a given word belonged. Following correct classification of this stimulus, the next word in the list was presented. The dependent variable was the number of words correctly classified in 60 s (thereafter transformed into a rate measure). As for Test 7, each subtask was performed on three separate occasions. Words were selected to represent categories on the basis of Rosch's (1975, 1978) research on prototypes.

Test 10: Multitask Word Classification. This was the word-classification component of the pairing of cards and words under the three multitask conditions. As in Test 8, participants performed 16 subtasks under each of the three experimental manipulations composing this ECT. Participants' output per 60 s was subsequently transformed into a rate measure (scaled in milliseconds).

Procedure

Total testing time per participant on these ECTs was between 6 and 7 hr. This was split over three experimental sessions that were generally spaced 1 week apart. Computerized ECTs were administered to small groups of 4 or 5 participants and lasted about 2–3 hr split over the first and (a portion of) the second session. The remaining experimental tasks were administered on an individual basis that covered the remainder of the second and third experimental sessions. Rest pauses of 10 min were given to all participants at the end of 50 min of work.

The order in which tasks were given in any test session was randomized, as were the conditions in each ECT. Arguments persist in the literature concerning this aspect of design (especially as it relates to individual-differences psychology [e.g., Jensen & Vernon, 1986]). However, this procedure was envisaged as going some way toward meeting the methodological concerns explicit in a critique of ECT research presented by Longstreth (1984, 1986).

Results

The data set generated by these 10 ECTs is clearly large. Across the various experimental conditions there were 273 measures of median (or mean) performance; 51 measures of intraindividual variability; and 9 measures each of slope, intercept, and model fit.[7] In addition, various mean median (or mean) and mean

[7]ECTs administered on a "face to face" basis resulted in more global measures of processing speed. For example, the card-sorting parameters were derived from the average number of cards sorted per unit of time. Consequently, these processing speed measures were based upon mean (rather than median) performance.

variability parameters were calculated both over conditions and throughout the entire task. Further still, measures of slope, intercept, and model fit were calculated as a function of an experimental condition (e.g., regression parameters of the competing task manipulations of card sorting calculated at 0, 1, 2, and 3 bits of information in the various secondary [word-classification] tasks). In order to facilitate a series of cogent arguments, the sections that follow largely contain summary statements of analyzed data sets that are pertinent to specific research issues. A complete listing of tables and figures of all variables examined (from which this commentary is derived) is, nonetheless, available on the World Wide Web at: http://www.psych.usyd.edu.au/difference5/papers/ects/index.html. Note that all information contained on this site is also available (upon request, in either electronic or printed form) as a technical report (Roberts, 2000).[8]

There are 128 tables and 45 figures presented in this report. Almost all are consequential to the arguments that follow. In order to facilitate discussion, this commentary is divided into three sections corresponding to the three main types of measure described in Table 1: central tendency, intraindividual regression, and intraindividual variability parameter. Nevertheless, in several instances, where this could be presented in an economical manner, relevant data are also presented in the passages that follow.

Central Tendency Parameters

Table 2 presents summary information pertinent to determination of the lawfulness (or otherwise) of measures of central tendency in DT and MT. The following is additional information required to correctly interpret this table:

1. Means of central tendency measures represent DT_X and MT_X values for specific tasks.

2. Reliabilities are presented for an entire task and as a range of values (because these were also calculated for specific conditions). In the case of computerized tasks, these reliabilities represent Cronbach alpha coefficients, and for the card-sorting and word-classification tasks, these reliabilities represent coefficients determined on the basis of the Spearman-Brown formula.

3. The modeling of information theory is for group data (rather than intraindividual regression parameters), because these analyses are the ones relevant to testing the efficacy of central tendency measures.

Mean (or Median) DT. As shown in the top half of Table 2, this parameter was consistently found to be reliable. Cronbach alphas ranged between 0.51 (Test 6)

[8]Both the Web site and accompanying technical report also contain specific commentary discussing the implications of analyses conducted within (and across) all ECTs, an extensive reference list, and further aspects of the methodology and rationale underlying the present investigation.

TABLE 2
Selected Statistics Associated With the Validation of Measures of Central Tendency (DT and MT)

Elementary Cognitive Task	*M* (ms)	*SD* (ms)	Overall reliability	Reliability: Range over conditions	Range of *r* across conditions	Group intercept (ms)	Group slope (ms)	Group model fit (*r*)
Decision time								
3. Single response	414.00	93.00	0.90	0.60–0.79	0.41–0.76	347.97	41.62	0.96
4. Tachistoscopic choice	509.00	124.00	0.99	0.96–0.97	0.64–0.96	349.70	79.50	0.99
5. Complex choice	768.00	260.00	0.98	0.60–0.92	0.66–0.84	40.82	158.58	0.97
6. Binary reaction	558.00	141.00	0.91	0.51–0.77	0.29–0.64	[a]	[a]	[a]
7. Single card	707.00	110.00	[a]	0.82–0.90	0.54–0.80	435.03	372.08	0.99
8. Multitask card	912.00	185.00	[a]	[a]	0.55–0.95	462.10	469.10	0.99
9. Single word	328.00	78.00	[a]	0.85–0.92	0.34–0.77	837.91	151.01	0.99
10. Multitask word	594.00	145.00	[a]	[a]	0.35–0.91	993.60	231.10	0.94
Movement time								
1. Fitts' movement	367.00	47.00	[a]	[a]	0.63–0.89	44.39	78.52	0.99
3. Single response	411.00	80.00	0.84	0.55–0.70	0.42–0.78	328.27	48.09	0.98
4. Tachistoscopic choice	609.00	165.00	0.98	0.91–0.95	0.38–0.97	326.60	141.50	0.99
5. Complex choice	454.00	92.00	0.93	0.55–0.82	0.54–0.71	300.29	33.61	0.88
6. Binary reaction	371.00	112.00	0.95	0.63–0.86	0.37–0.66	[a]	[a]	[a]
7. Single card	462.00	86.00	[a]	0.90–0.93	0.76–0.82	[a]	[a]	[a]
8. Multitask card	482.00	96.00	[a]	[a]	0.55–0.95	[a]	[a]	[a]
9. Single word	819.00	47.00	[a]	0.84–0.85	0.64–0.66	[a]	[a]	[a]
10. Multitask word	895.00	78.00	[a]	[a]	0.35–0.91	[a]	[a]	[a]

Note. The Joystick Reaction Task gave measures of global reaction time and hence is not included in this table. DT = decision time. MT = movement time.
[a]Indicates analyses that could not be conducted (or would have been inappropriate).

and 0.97 (Test 4) within bit levels, with overall reliability exceeding 0.90 for all tests. These DT parameters also exhibited the following properties:

1. A high degree of fit to the Hick-Hyman law. Although each of the tasks clearly involved different cognitive requirements, model conformity exceeded 0.94 for all ECTs in which a relationship between DT and bits was hypothesized. To highlight the degree of model conformity evidenced in these ECTs (beyond that already given by Table 2), a graphical representation of data provided from Test 5 is reproduced in Figure 2.

2. Within each ECT, close correspondence with results reported in the literature examining group effects in DT. For example, the rate of transmission (calculated as the inverse of the slope constant) in Test 7 was 2.69 bits/sec, a value that is close to that reported by a number of investigators employing the card-sorting methodology (e.g., Crossman, 1953; Roberts et al., 1988, 1991). Similarly, response latencies to brief and long exposure intervals in Test 4 (899 ms vs. 939 ms, respectively) were very close in magnitude to that obtained by experimentalists who have investigated this phenomenon (e.g., Christ, 1970; Kaswan & Young, 1965). Indeed, almost without exception, the results presently obtained with the median (or mean) DT variables were readily interpretable in terms of

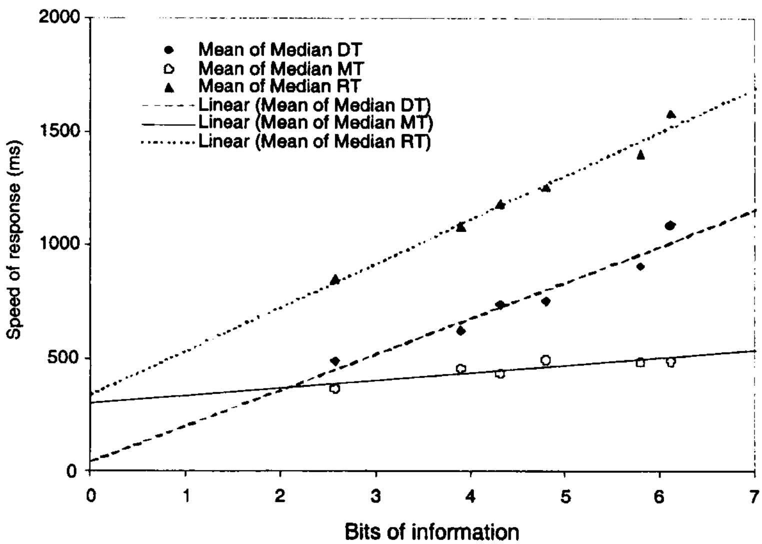

FIGURE 2. Mean of median speed measures (i.e., DT, MT, and RT) as a function of bits of information derived from Test 5, Complex Choice Reaction Time.

previous experimental findings. This outcome provides fundamental evidence that confirms that these cognitive paradigms are behaving as expected for measures of central tendency.

3. Significant effect of stimulus-response (S-R) codes (e.g., light-keypad [Tests 3, 5, 6], word-voice [Tests 9-10], etc.) employed in each ECT on RT, such that differences in slope and intercept functions between tasks were as predicated in the literature (e.g., Brainard, Irby, Fitts, & Alluisi, 1962). Note that the nature of the S-R code, although often acknowledged for its importance in cognitive models of RT (e.g., Teichner & Krebs, 1974, who devote much of their review of choice RT studies to this factor), has received scant attention in the individual-differences literature.

4. Measures of central tendency exhibiting robust measurement properties. Application of conjoint measurement procedures (e.g., Luce & Tukey, 1964; Michell, 1990; Stankov & Cregan, 1993) within a selection of the ECTs (in particular, Tests 7–10) revealed that mean DT variables consistently met the conditions for the assumption of quantitative structure. This finding is not inconsequential given the difficulties often encountered in psychological investigations with the measurement properties of the variables that are examined (Michell, 1990).

5. Moderate-to-high intercorrelation between conditions, with simplex patterns actually occurring in many of these data sets. To account for the lawfulness of this phenomenon, Jensen (1987) has proposed an "overlap model" that is based on the idea of common elements between variables. This model subsequently predicts the actual magnitude of correlation between different set sizes, according to the formula: n_x/n_y (where n_x and n_y are the set sizes of the two conditions being compared). In the present study, conformity to the overlap model was adequate across the majority of data sets (*r*s generally exceeded 0.70).

The current findings also support the construct validity of the DT parameter. Thus, the average correlation between the DT_X of any two ECTs of the battery was 0.36. This coefficient was reduced somewhat by lower correlations between vocal and motor response (than those obtained within the same response domain). Indeed, the most salient feature of these ECTs accounting for the magnitude of correlation coefficient was the nature of the S-R codes. That finding suggests that attention can (and should) be afforded to structural models of processing speed (see Carroll, 1993; Roberts, 1997a; Roberts et al., 1999; Roberts & Stankov, 1999).

Mean (or Median) MT. As can be observed from the bottom half of Table 2, the MT parameter (like DT) was reliable. Cronbach alpha ranged between 0.55 (Test 3) and 0.95 (Test 4) within conditions, with overall reliability exceeding 0.80 for all ECTs. A somewhat unexpected finding was the presence of a linear relationship between MT and bits in each of the RT tasks (*r*s ranging between 0.88 [Test

5] and 0.99 [Tests 4 and 5]). This outcome is not to be expected on the basis of the information theoretic principle describing the function of MT and stimulus information. This principle, known as Fitts' law, states that: $MT = k \log_2 (A/W + 0.5)$. Because neither target width (W) nor target distance (A) was manipulated in any ECT (other than Test 1), it follows that some DT processes entered this component of performance in many of the tasks (see Smith, 1989). Notwithstanding, an indication of the magnitude of this effect could be obtained since Test 1 involved a "pure" manipulation of MT, and Test 6 always required the same type of movement. Findings indicate the intrusion of DT into MT is not pronounced in many of the ECTs for three reasons:

1. The slope of MT and bits is lower than the corresponding slope of DT on bits (see Figure 2) and, considering facets of each task's experimental design, not that discrepant from zero (see Roberts, 2000).
2. The MT_X value obtained in Test 1 is remarkably close to the corresponding parameter obtained in each of the remaining experimental tasks if one chooses to determine the information in these tasks by adopting Fitts' law. For example, measuring target distance and target width for each ECT and entering it into the information theory formula for MT gives an average information value that is close to the average value over the five conditions of Test 1. Indeed, that correspondence is all the more compelling when allowance is made for target tolerance resulting from the width of the finger pad (see Hoffmann & Sheikh, 1991).
3. The values of MT obtained in Test 6 are not seriously discrepant from those obtained in the other computerized ECTs.

Test 1 alone provides meaningful information on the adherence of mean MT data to a simplex pattern of intercorrelation since, as noted previously, this was the only ECT in which task difficulty was manipulated during the MT phase. This pattern was found without a single violation occurring across the 5×5 correlational matrix derived from this task (see Roberts, 1997b). Note also that in Test 1, the mean results obtained with MT were remarkably close to those obtained previously by researchers employing this type of paradigm. For example, the rate of transmission for the present group was 12.7 bits/s, a value that is close to that obtained by Fitts (Fitts, 1954; Fitts & Petersen, 1964) and others working in the area of motor performance (e.g., Welford, 1968; Welford, Norris, & Shock, 1969).

Furthermore, the current findings support the construct validity of the MT parameter. The average correlation between the MT_X of any two ECTs was 0.38. Unlike DT, this coefficient was remarkably stable across ECTs that involved experimental manipulations conducted within different stimulus-response domains. Of critical importance, MT_X shared a low average correlation of 0.16 with DT_X across the battery of ECTs. It would thus appear that these two constructs are, in the main, structurally independent.

Mean (or Median) RT. Not surprisingly, since it was most often obtained as a composite of DT and MT, analyses conducted with the RT parameter generally mirror the aforementioned results (see also Figure 2). However, previous modeling of MT data makes it paramount that consideration be given to the RT variable (rather than DT) when considering intraindividual regression parameters. That focus is required because it would appear that there are individual differences in the strategies participants adopt during the MT phase: Some individuals adopt a hovering technique, and others fully process the information before making an aimed ballistic movement (Smith, 1989).

Intraindividual Regression Parameters

Means and standard deviations for intraindividual regression parameters (i.e., intercept, slope, and model fit statistics) are presented in Table 3. Although none of these parameters appear particularly problematic at first blush (with the exception of Test 2), more detailed analyses reveal a number of inconsistencies. For example, in Test 1 some 25% of the sample provided negative intercept values.[9] In Test 3, when four data points were used, only 60% of the participants provide rank orders consistent with the Hick-Hyman law (Roberts, 2000). This is increased to 83% when only 3 data points are used—a value consistent with that reported previously (e.g., Jensen, 1987), such that the present result cannot simply be attributed to procedural (or sampling) differences.

The average correlation between intraindividual intercept (i.e., RTa) parameters from the battery of ECTs is 0.19. The magnitude of even this low correlation is artificially inflated by high coefficients that are obtained between single and multitask versions of card sorting and word classification. In a like manner, the average correlation between slope (i.e., RTb) measures is low ($R = .11$). These findings question the construct validity of both of these measures.

As it turns out, these parameters are even more problematic than suggested by these intercorrelations alone. Thus, in one or two tasks where model fit is high across all participants (e.g., Test 7, where 99% of the sample provided rank orders consistent with the Hick-Hyman law), the correlation between RTb and DT_X tends to approach unity. However, in other paradigms this correlation is moderate (e.g., Test 5, $r = 0.61$) and still others it is low (e.g., Test 3, $r = 0.05$). Similarly, the correlation between intercept and slope in RT fluctuates markedly across

[9]The finding of a negative intercept in this task is not without precedent in the experimental literature (see Annett, Golby, & Kay, 1958) and therefore cannot simply be attributed to inadequacies in the experimental design.

[10]A perusal of the literature reveals this outcome to be prevalent in research involving ECTs. For example, the correlation between slope and intercept in DT is high and negative in some studies (e.g., Jensen, 1982, where $r = -.72$), though at other times it tends toward zero (e.g., Vernon, 1983, where $r = -.07$).

TABLE 3
Summary Statistics for Intraindividual Regression Parameters

Elementary Cognitive Task	*M*	*SD*
Intercept		
1. Fitts' movement	45.80	75.60
2. Joystick reaction	343.70	118.00
3. Single response	676.20	144.90
4. Tachistoscopic choice	676.30	247.20
5. Complex choice	347.00	258.40
7. Single card	434.90	79.60
8. Multitask card	462.30	99.90
9. Single word	883.30	107.00
10. Multitask word	1224.50	150.50
Slope		
1. Fitts' movement	78.00	39.60
2. Joystick reaction	58.60	47.30
3. Single response	89.20	47.50
4. Tachistoscopic choice	220.80	113.60
5. Complex choice	199.00	110.40
7. Single card	372.20	74.50
8. Multitask card	469.20	109.30
9. Single word	131.30	53.60
10. Multitask word	132.60	59.80
Model fit		
1. Fitts' movement	.97	.03
2. Joystick reaction	.60	.24
3. Single response	.82	.19
4. Tachistoscopic choice	.92	.12
5. Complex choice	.86	.14
7. Single card	.98	.01
8. Multitask card	.99	.01
9. Single word	.96	.08
10. Multitask word	.96	.08

ECTs (*r*s ranging from –.68 [Test 4] to .00 [Test 8]).[10] Finally, some commentators have suggested that the degree of model fit might, in itself, provide a meaningful individual-differences variable (Eysenck, 1987). However, the average correlation between any two indices of model fit in this battery was .04.

Intraindividual Variability Parameters

Table 4 includes a number of statistics relevant to assessing the validity of intraindividual variability in DT (sdDT) and MT (sdMT). In this instance, this includes descriptive statistics, correlations within conditions, indices of model fit for group data, and correlations across ECTs.

A good deal of debate in the literature has been devoted to the conceptual status of the sdDT parameter (e.g., Jensen, 1987, 1992). However, the present results cast doubts on the validity of this measure. Problems with intraindividual variability parameters found in the present study include each of the following:

1. Variability in DT shares a linear relationship with measures of set size both within and between participants, across all ECTs (*r*s exceeding 0.88 [cf. Jensen, 1987]). Noting the logic given in the method section for the presence of simplex pattern, it follows that the sdDT parameter should reveal a simplex pattern over set size. However, correlations across conditions are often low. More critically, simplex is not observed in any data set of the ECTs presently investigated.

2. Researchers who have focused upon mean intraindividual variability in DT over set size (i.e., $sdDT_X$ [e.g., Jensen, 1992]) may have implicitly acknowledged the preceding anomaly. However, data obtained from the present study portray this measure in an equivocal light for a number of other reasons as well. In particular, intercorrelations between sdDTs of every ECT are quite low ($R = .26$). Furthermore, correlations between $sdDT_X$ and DT_X at each set size are observed to be highly variable across ECTs (i.e., sometimes $sdDT_X$ is highly correlated with the simplest condition [e.g., Test 3], at other times, with the most complex conditions [e.g., Test 5]).

3. Factor analysis of intraindividual variability measures fails to show this as a meaningful individual-differences construct. Similar results have been reported by Carroll (1993, p. 485). This outcome also happens to hold true when intraindividual variability measures of speed in psychometric tests are examined, rather than performance in more elementary cognitive tasks (see Roberts, 1995; Stankov, Roberts, & Spilsbury, 1994). It would appear, across disparate paradigms (assessing a range of cognitive processes), that central tendency parameters are consistently more dependable measures of factors than intraindividual variability parameters.

4. The correlation between $sdDT_X$ and DT_X measures of the present study were substantial ($R = .69$).[11] This finding is exactly what would be predicted on the basis of a serial model of choice reaction time (McGill, 1963). In turn, this would appear to explain why $sdDT_X$ measures share substantial correlation ($R = .41$) across ECTs and perhaps also why $sdDT_X$ measures have shared moderate (to high) correlation with intelligence measures in the past. Consistent with this set of propositions, $sdMT_X$ measures (a) are largely independent of MT_X parameters ($R = .15$); (b) share near zero correlation across ECTs ($R = .11$); (c) should probably

[11]It might be objected that this outcome occurs because the $sdDT_X$ and DT_X parameters are based on the same data set. However, it turns out that when these measures are independently assessed (i.e., from odd and even trials) they remain correlated and do not separate into distinct factors. Moreover, the fact that $sdMT_X$ and MT_X do not share substantial correlation (however assessed) is an anomaly that needs to be addressed by proponents of models based on intraindividual variability parameters.

TABLE 4
Various Statistics Associated With the Validation of Measures of Intraindividual Variability in Performance Speed (i.e., sdDT and sdMT)

Elementary Cognitive Task	*M* (ms)	*SD* (ms)	Range of *r* across conditions	Group intercept (ms)	Group slope (ms)	Group model fit (*r*)	Correlations between tasks on corresponding intraindividual variability measures		
							2	3	5
sdDT									
2. Joystick reaction	46.40	17.90	0.11–0.48	39.57	1.51	0.71	1.00		
3. Single response	175.60	146.30	0.06–0.50	65.50	19.80	0.88	0.36	1.00	
5. Complex choice	235.80	102.00	0.13–0.46	145.99	2.76	0.89	0.32	0.54	1.00
6. Binary reaction	272.80	191.80	0.01–0.44	[a]	[a]	[a]	0.40	0.49	0.37
sdMT									
3. Single response	411.00	80.00	–0.10–0.07	69.50	19.00	0.90	[a]	1.00	
5. Complex choice	454.00	92.00	–0.02–0.31	272.00	5.82	0.91	[a]	0.02	1.00
6. Binary reaction	371.00	112.00	–0.12–0.19	[a]	[a]	[a]	[a]	0.12	0.19

Note. In Test 2, the actual measure is intraindividual variability in reaction time (because of the design of this task). Tests not listed in this table were those where intraindividual variability parameters were not calculated.
[a]Indicates analyses that could not be conducted (or would have been inappropriate).

not even be derived given the near zero (and sometimes, negative) correlations observed across conditions in Table 4 (see column 4); and (d) have not resulted in one significant correlation with intelligence measures in any study published to date (e.g., Jensen, 1982; see also Roberts, 1995).

5. The aforementioned findings suggest a source of inconsistency in the treatment of intraindividual variability measures, and the sdMT parameter (in particular) seems poorly understood. Recently, there has been renewed interest in MT (e.g., Buckhalt, Reeve, & Dornier, 1990; Roberts, 1997b). However, no researcher has offered a reasonable hypothesis as to why the sdMT parameter does not correlate with intelligence measures. And yet, if intraindividual variability is a neurophysiological phenomenon (as is claimed), why is it not the case that this measure correlates with psychometric indices? Note, a motor-output variability hypothesis has been offered in the human performance literature that links variable performance in MT with errors in neural transmission (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). It remains unclear why theories emanating from relationships between intraindividual variability and intelligence have not been rigorously tested using the type of tasks devised by Schmidt et al. (1979). This shortcoming is especially curious given that such paradigms appear (a) to provide data that are more reliable and (b) to closely represent the types of biological mechanisms that are advocated in contemporary theories of individual differences.

In sum, there are considerable anomalies generated by the intraindividual variability measures. It may of course be objected that these outcomes follow from the simple fact that this parameter is highly unstable (see in particular, Jensen, 1992). Although this may be true, it leaves the construct open to widely different interpretations from study to study. Moreover, the low stability found with RT tasks seems a pitfall that those interested in exploring the theoretical importance of intraindividual variability might avoid by more careful task selection. These problems would appear exacerbated by the fact that there remains little attempt to link intraindividual variability measures to theories of response selection in the available individual-differences literature (see e.g., Luce, 1986; Wing & Kristofferson, 1973).

Discussion

In the present study, we systematically examined a large number of ECTs, in each instance applying consistent analytical principles to a given paradigm. In so doing, our aim was to examine the empirical efficacy of key parameters that, in turn, have lent themselves to a variety of models linking intelligence and processing speed. This interest was motivated by a concern that unresolved anomalies exist within the cognitive-correlates approach to individual differences. It was not our intention to argue from a position more relevant to philosophical principles underlying measurement theory (however implicit this is in our use of conjoint measurement [see Michell, 1990]). Rather, our main concern was to assess measures that have not yet been subjected to basic validation procedures considered pivotal in the investigation of psychological constructs.

These issues appear to have arisen largely because careful attention has not been afforded the microstructural properties of ECTs. For example, slope DT parameters do not always demonstrate higher correlation with intelligence measures than do MT, intraindividual variability measures, or the like. Unfortunately, on occasion, acceptance of an alternative parameter has seemingly involved ad-hoc justification. That tendency may have been exacerbated by employing alternate measures chosen on the basis of post hoc rationale (i.e., after the inspection of a large list of correlations between intelligence test scores and the alternative parameters derived from a given ECT). Although it is hoped that these questionable practices do not occur, either possibility must be seriously entertained because such an impression is easy to gain from a perusal of the relevant literature (cf. Jensen, 1987, and in particular, Table 25, pp. 158–159).

Measures of Central Tendency

It has been observed in previous research that measures of median DT are reliable (e.g., Widaman & Carlson, 1989). The extent to which this was evidenced across a variety of ECTs is impressive. Note also that each measure of central tendency subscribed to various lawful principles such that there was an increase in correlation within the conditions of each ECT. Further, a high degree of conformity to the Hick-Hyman law was obtained in those instances where group data were analyzed. In certain circumstances, where this may not have been evidenced as clearly as others, a ready explanation is available: The Hick-Hyman law is not a universal phenomenon but rather a statement that describes performance under ideal conditions (Welford, 1968).

Intraindividual Regression Parameters

Interest in the slope of DT (which originally spawned interest in the Hick paradigm [Roth, 1964]) has waxed and waned considerably over the past two decades. An attempt to provide a better understanding of this construct was made by Barrett et al. (1986). These authors examined regression parameters as a function of differential degrees of intraindividual model fit. Their results were suggestive of the need to cull individual participants not fitting the Hick-Hyman model since these simply add noise to the data, thereby attenuating theoretically meaningful correlations (Smith, 1989).

On the basis of the present findings, culling would seem inappropriate, largely because intraindividual regression parameters have uncertain empirical status.[12] Our analyses indicated that the meaningfulness of the slope of RT is largely an artifact caused by selecting an insufficient number of data points to have made definitive statements about intraindividual fit to the Hick-Hyman model. It should be emphasized that no previous studies have examined this model with respect to more than four levels of stimulus information. In the present study, when five data points were examined in paradigms that, in principle, should have provided high subject conformity, the results were surprisingly poor. That finding could be attributed neither to methodological inadequacies nor to sample characteristics—by selecting the same number of data points as is most frequently reported in the literature, the percentage of participants fitting the model was shown to be high. The failure of individual participants to conform to underlying information-processing models is probably common to many ECTs and would certainly seem to require more careful attention than has been given in the past (Lohman, 1994, 1999).

The consistent failure of individual participants to fit the Hick-Hyman model questions those theoretical models that have suggested that individual differences in rate of mental processing are responsible for individual differences in intelligence (e.g., Bates & Stough, 1997, 1998; Jensen, 1982, 1998). The current study also examined the claim that differential degrees of model fit constitute a reliable individual differences variable (Eysenck, 1987). Demonstration of this phenomenon would have made propositions concerning the lack of evidence for intraindividual regression parameters irrelevant. However, no evidence for significant correlation between intraindividual fit to the Hick-Hyman model was found across any pairing of the ECTs that were presently examined.

Intraindividual Variability Measures

Measures of intraindividual variability and their correlation with intelligence appear to have contributed greatly to a renewed interest in RT (Jensen, 1992, 1993). In the present study, however, the empirical status of intraindividual variability measures is shown to be equivocal. In particular, sdDT fails to exhibit a simplex pattern, although $sdDT_X$ measures are neither independent from more generic DT_X parameters nor adequately defined by their subcomponents. Indeed, these parameters generate substantial anomalies that are difficult to reconcile with their purported status.

Elsewhere Jensen (1987) has claimed:

[12]The interpretation of culled data is, irrespective of the present outcome, more problematic than its advocates would have readers believe. The problem rests with the conclusions that may be drawn. Any inferences become restricted to a sub-sample of the population (i.e., it limits the population with respect to intelligence measures). This state of affairs represents something of a trade-off between theoretical explanation and generality. In other words, theories should apply to the intelligence of the people, not to a subset who fit a theoretical model.

> Since sdDT increases linearly as a function of set size, with increasing set size one should predict a greater opportunity for individual differences in the oscillation process hypothesized to underlie both sdDT and g to be increasingly manifested, thereby making for a monotonically increasing (negative) correlation between sdDT and g as a function of set size. This prediction [has] not been borne out in the least. . . . This is the only really substantial anomaly for the oscillation model. (p. 166)

Findings in the present study would appear to constitute further anomalies in the neural oscillation model that Jensen (1987) has proposed. Indeed, within the individual-differences literature, several theories have been based on the correlation that sdDT parameters share with intelligence measures. In light of the present results, critical consideration is given both to the *neural oscillation* model and to a theory that posits errors in neural transmission.

Neural oscillation. This model involves the notion that neural oscillation may be an important physiological process underlying intelligence (Jensen, 1979, 1992). Importantly, several eminent physiologists (including Crick [1993]) subscribe to a similar concept. However, it remains unclear as to why neural oscillation needs be connected to measures of intraindividual variability in processes linked to speed. It seems equally plausible that neural oscillation be associated with measures of speech production or some other nonspeeded aspect of cognitive performance.[13] Good thinking implies making fewer errors, and speed cannot always be beneficial in this regard. Furthermore, the operations of a cognitive system are dependent on both the speed of neural oscillation and the wiring of various subcomponents (Rabbitt, 1994; Stankov & Roberts, 1997). In and of themselves, neural oscillations do not determine the efficiency of the cognitive system; conceivably, efficiency depends critically also on many hardware and software features (Sternberg, 1986).

Errors in neural transmission. This model states that "noise" within the information-processing system (due to errors in synaptic transmission [Eysenck, 1987]) is the critical phenomenon contributing to individual differences in intelligence. Since good thinking depends on being able to make as few mistakes as possible, this explanation of the link between measures of intraindividual variability and intelligence has some intuitive appeal. However, in a recent study (Stankov et al., 1994) and in reanalyses conducted by Carroll (1993, pp. 484–485), the correlation between measures of central tendency and intraindividual variability in performance was found to be high. Therefore, it would seem

[13]As an analogy, faster computers (i.e., those accessing RAM at 66 MHz rather than 32 MHz) perform more operations at greater speed but nonetheless are still prone to make errors. Perhaps better image resolution or finer sound reproduction can be achieved with faster computers; speed of doing computations is just one of the consequences of faster neural oscillation.

injudicious to claim that these processes are in any way different. Findings reported in the present study reinforce this view (see also Brody, 1992, pp. 52–53). Failure to establish correlations between sdMT and psychometric measures should also cause some concerns for the proponents of this theoretical position, more especially because similar neurophysiological models have been constructed around variability in motor output.

Future Directions

It would be remiss to suggest that the present findings are simply negative, because measures of central tendency in the various ECTs are shown to be quite lawful. The question then is how those researchers interested in using ECTs to uncover critical properties of the human organism might proceed in the future. One answer is to look toward more contemporary models of RT rather than "home-spun" theories or otherwise unverified statistical postulations. It must be remembered that the majority of research paradigms employed herein have a long (and somewhat checkered) history in the experimental literature (see e.g., Kornblum's [1967, 1968] critique of the Hick paradigm). In part they are still employed by experimentalists, but the models underlying them have generally gained in breadth and sophistication beyond the rather simple (though undoubtedly important) information theoretic principles that Hick, Hyman, and a host of others utilized during the zenith of this conceptual framework (cf. Neisser, 1967).[14]

One engaging possibility rests with the fact that there are notable differences in mean performance across ECTs of the present study. These differences are seemingly dependent on the stimulus-response codes that underlie each task. Interestingly, the study of these codes (i.e., investigation of S-R compatibility effects) is currently one of the emerging areas of both cognitive and human factors psychology. In particular, Kornblum and his associates (see e.g., Kornblum, 1992, 1994; Kornblum, Hasbroucq, & Osman, 1990; Kornblum & Lee, 1995; Wang & Proctor, 1996) have been engaged in a generative research program associated with what they term the *dimensional-overlap model*.[15] The present battery of ECTs may be thought of in this context since the S-R codes are notably disparate (i.e., they involve both congruent and incongruent mapping). Importantly, the mean para-

[14]We do not believe this criticism should be reserved simply for information theory approaches to ECTs. Thus, it appears to also be true of disparate theories that make use of Sternberg's (1969) scanning paradigm, the Stroop paradigm, and many others. It is worth noting that the dimensional-overlap model explicated within these passages provides a unifying taxonomy and theoretical framework for interpreting each of these types of effect.

[15]Dimensional-overlap is defined as "the degree to which two sets of items have properties or attributes in common, and the degree to which such attributes are similar to one another" (Kornblum, 1992, p. 749). The greater the dimensional overlap, the greater the

meters of each ECT seem to be predicted by this model, as are correlations with measures of intelligence (Roberts, 1997c; Roberts & Stankov, 1995, 1999). Perhaps of equal importance, correlational and factor analyses of these ECTs support the differentiation of factors by the principles explicated in the dimensional-overlap model (Roberts et al., 1999; Roberts & Stankov, 1999).

There are several interesting features of the dimensional-overlap model that may readily appeal to psychologists interested in individual differences. For one, it has important conceptual links to models of attention, and despite changing terminology (resources, capacity, workload, or the like), attention remains closely linked to intelligence (e.g., Hunt & Lansman, 1982). Another interesting aspect of the dimensional-overlap model is that it contains within its framework a biological subtheory that suggests that compatible tasks require different neurophysiological pathways for optimal performance than do incompatible tasks. Indeed, there are several important studies with both animals (e.g., Georgopoulos et al., 1989) and humans (e.g., DeJong, Liang, & Lauber, 1994; Eimer, 1995) supporting that distinction. Although direct studies of the dimensional-overlap model remain to be conducted by psychologists interested in understanding individual differences in intelligence, the available biological evidence lends itself to a provocative question. To what extent is it justifiable to choose highly compatible ECTs (such as those often employed in individual-differences research) and then lay claim to the fact that significant biological concomitants have been isolated?

Practice Effects: Practical and Conceptual Implications

Finally, it would seem expeditious to comment on the effects practice might have in the present investigation since this factor may operate as a troublesome confound (e.g., Bittner et al., 1986). This potential problem is emphasized by established interactions between cognitive ability level and number of trials (e.g., Ackerman, 1987; Fleishman & Hempel, 1954; see Schwartz, 1981, for an alternative perspective). Indeed, the negative results with several parameters examined in this report might plausibly be attributed to the fact that participants experienced differential rates of improvement over experimental sessions. Moreover, because of the large number of parameters measured in this study, the number of

reaction time difference between congruent (e.g., a vocal response of either "one" or "two" to the digits "1" or "2") and incongruent mappings (e.g., a vocal response of "one" to "2" and "two" to "1") (Wang & Proctor, 1996). The model postulates two response routes: Translation of information into a response by a response identification mechanism and automatic activation of the corresponding response. In turn, the model "asserts that the difference between congruent and incongruent mapping conditions reflects the action of facilitation and interference processes" (Kornblum, 1992, p. 756). In other words, "the greater the dimensional overlap . . . the greater the facilitation with congruent mapping and the greater the interference with incongruent mapping" (Kornblum et al., 1990, p. 262).

practice trials was (intentionally) made smaller than would normally be implemented in "classical" experimental paradigms.[16] Could the present results simply be an artifact of this methodological limitation?

There are a number of reasons why that interpretation of the present findings would appear ill founded. In particular, all participants were given ample time to familiarize themselves with the typical apparatus and procedures underlying each ECT in the first test session. The main aspect of computerized testing was general to all such tasks: responding (usually by key press) to some stimulus (usually a light) from a home key to that stimulus's representation. Task variations beyond this general procedure were, by and large, slight (i.e., task demands shared a great deal of overlap).[17] Thus, each trial served to familiarize the participants (in cumulative fashion) with a given apparatus and procedure as they participated interactively with each task. Because the order of task presentation was randomized, more global practice effects were controlled for as far as possible. The fact that each of the computerized ECTs exhibited impressive reliability (in spite of the small number of practice trials and randomized ordering) is indicative of the fact that entrainment effects were negligible. Equally important, the mean results obtained in each ECT were consistent with findings reported in the experimental literature suggesting that neither methodological artifacts nor differences in training protocol could account for the present findings.

Note also that in five of the paradigms employed in the investigation (i.e., single and multitask card-sorting, single and multitask word-classification, and Fitts' Movement Task) participants performed each condition according to a "subject-paced" regime. Thus, the results reported (which were sometimes based on two or three replications) actually represent the mean of performance over literally hundreds of experimental trials. The problematic parameters identified in these tasks (i.e., intraindividual variability, intraindividual regression measures) are precisely those identified in the computerized ECTs, lending credibility to the conclusions presented throughout this article.

Even so, practice effects are likely to remain a concern for the individual-differences researcher when it comes to interpreting performance in ECTs. The point has been disregarded in strict processing speed accounts, which ignore the experimental finding that, with sufficient practice, reaction times for degrees of choice below 10 can be brought to the same level as a 2-choice task (Mowbray,

[16]This was inevitable due to the logistics of the study that already demanded much of the participants' time.

[17]It could be objected that any task variation should have been accompanied by extensive practice sessions. In principle, this is certainly true. Nevertheless, the intrusion of practice effects seems unlikely to provide even a partially satisfactory account of present findings. Thus (in addition to the findings obtained with mean structure), participants reported being aware of the task requirements even prior to performing an ECT once they had completed one task type.

1960; Mowbray & Rhoades, 1959). The model of stimulus-response compatibility alluded to in the later passages of the present article acknowledges the importance of such effects.[18] Most important, experimental studies have demonstrated that the differences between compatible and incompatible tasks are not differentially affected by practice (Kornblum et al., 1990). For example, Fitts and Seeger (1953) report a study in which six participants performed three tasks having different S-R ensembles over a period of 1,500 trials. The results showed that despite overall RT decreasing throughout the training period for all three ensembles, the magnitude of difference (between the most and least congruent mappings required within tasks) remained constant.

Conclusion

The most reliable and valid constructs obtained from ECTs are measures of central tendency. These are shown to exhibit a remarkable degree of lawfulness across 10 ECTs. As such, these parameters are currently being used to develop a taxonomic model of processing speed. Preliminary analyses indicate interpretable first- and second-order DT and MT factors (Roberts et al., 1999; Roberts & Stankov, 1999). These constructs have also been used to demonstrate the fact that processing speed measures share differential relationships with the various cognitive abilities postulated under G_f/G_c theory (Roberts & Stankov, 1995, 1999).

Contrary to the lawfulness that is found with central tendency parameters (and the clarity they bring to important research questions), intraindividual regression and variability measures have equivocal empirical status. Because of this finding, several currently popular explanatory models of human intelligence (e.g., neural oscillation) would appear, at best, to require urgent reformulation. Indeed, it might be argued that it is inappropriate to attempt to salvage these models, and thus, that it is necessary to look toward new models to account for correlations between ECTs and intelligence. One interesting possibility rests with the dimensional-overlap model of RT introduced briefly in this article.

Collectively, these findings also have important implications for applied psychology. ECTs are becoming increasingly popular as both selection and assessment devices (e.g., Ree & Carretta, 1996). Until several critical issues surrounding performance in ECTs are resolved, the notion that these paradigms represent more theoretically sophisticated instruments should be treated with suspicion.

[18]Models of stimulus-response compatibility also acknowledge that different stimulus-response mappings are differentially sensitive to practice effects (see e.g., Teichner & Krebs, 1974). Of interest to findings reported in the present study, the paradigm that has consistently been shown to be the least susceptible to practice effects employs the light-keypad setup.

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