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MENTAL SPEED

On Frameworks, Paradigms, and a Platform for the Future

VANESSA DANTHIIR

RICHARD. D. ROBERTS

RALF SCHULZE

OLIVER WILHELM

Although once given scant treatment, the importance attached to "mental speed" in providing improved understanding and measurement of intelligence is growing. The veracity of this statement is evidenced by a number of observations. For instance, several broad factors representing mental speed abilities are currently incorporated within two important, structural models of cognitive abilities: Gf-Gc (see, e.g., Horn & Noll, 1994) and three-stratum (e.g., Carroll, 1993) theory. With respect to the latter of these conceptualizations, Carroll (1993) notes, "If any broad taxonomic classification of cognitive ability factors were to be formulated, in fact, it might be one based on the distinction between level [accuracy-based performance] and speed" (p. 644). Another reflection of the growing import of mental speed is the fact that almost all prominent multiple-aptitude batteries (e.g., the Armed Services Vocational Aptitude Battery [ASVAB], U.S. Department of Defense [DoD], 1984) and intelligence test batteries (e.g., Berlin Intelligence Structure test [BIS], Jäger, Süß, & Beauducel, 1997 [see also Chapter 18, this volume]; Wechsler Adult Intelligence Scale–III, Wechsler, 1997; Woodcock Johnson Tests of Cognitive Ability III, Woodcock, McGrew, & Mather, 2001) include the assessment of mental speed as an important operational and conceptual undertaking. In a

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slightly different vein, Eysenck (1995) refers to "an explosion of experimental studies into the speed of mental processes" (p. 225). In turn, this research activity has resulted in the now well-replicated finding of a moderate negative correlation between reaction time (RT) indices and measures of intelligence.

Despite promises offered by mental speed research, understanding of the construct in differential psychology appears less than adequate. Numerous constructs falling under the rubric of "mental speed" have been investigated, and yet there is a dearth of information regarding how these different types of speed are conceptually and empirically interrelated. In short, although much data on mental speed and related constructs exist, an integrative, conceptual framework is lacking. Clearly frustrated by this status quo, Carroll (1993) has voiced concerns regarding the poor treatment given to mental speed in extant research, such that many of his comments surrounding the structure of mental speed are guarded.

Although it is beyond the scope of a single critical review to redress these imbalances, in this chapter, we aim to provide the foundations for a more integrated perspective on mental speed. To this end, we first consider the main ways in which mental speed has previously been conceptualized within the field of intelligence, focusing on two approaches, distinctions between them, and ways in which a rapprochement might be breached. We then move on to describe several studies that allow some insight into the structure of mental speed before providing an overview of a variety of different indicators of mental speed and related constructs. We also examine the implicit influence of speed within the constructs of reasoning ability and working memory. In the penultimate section to this chapter, we raise issues that we consider necessary to address in the future, so as to further understanding and improve measurement of mental speed, before closing with some summary statements.

Explanatory Versus Descriptive Approaches to Mental Speed

The two distinct viewpoints on mental speed that have emerged from within individual differences research can be termed the *explanatory* (what Conway might call *reductive*; see Chapter 4, this volume) and the *descriptive* viewpoints. The distinction is more than one of arbitrary labels as it defines two quite different ways of investigating the construct empirically. The first approach has, at its heart, the idea that an explanatory definition of intelligence will emerge by investigating (and finding) basic cognitive processes related to individual differences in traditional accuracy-based measures of psychometric intelligence. This approach has drawn inspiration from processes emphasized by experimental cognitive psychology. Inside this framework, the construct of mental speed is considered to reflect basic processes comprising individual differences in intelligence test scores (Stankov & Roberts, 1997). By contrast, the descriptive approach considers mental speed in the context of numerous broad cognitive abilities, many of which have been identified by attempts to derive the structure of human cognitive abilities from examination of the relationships between cognitive tasks.

Beside the impetus that has driven these research programs, several other pertinent features typify each of these two approaches. The explanatory approach primarily focuses on the speed at which a task (generally presented via computers or special apparatus) is performed and uses correlational or regression techniques. By contrast, the descriptive approach typically (although not always; see Carroll, 1993, for exceptions) focuses on measures of accuracy (derived from paper-and-pencil measures) and factor-analytic methods. Furthermore, within the explanatory framework, a few simple psychological tasks are generally related to a few (sometimes only one) psychometric measures. In contradistinction is the large number of more complex measures that are investigated in attempting to determine the factor structure of cognitive abilities within the descriptive framework. Arguably, the primary method of investigating mental speed within individual differences research has been the explanatory approach; however, within the descriptive approach, investigations into mental speed have importantly resulted in the incorporation of speed factors into structural models of individual differences.

Before turning to a more detailed description of research conducted within these two research "traditions," we mention briefly a third framework in which mental speed constructs are investigated, something that might be labeled the *response time modeling approach.* It is similar to the previous approaches in that the principal variable of interest is the time to initiate and make a (correct) response to a cognitive task. However, some important differences are also worth noting. First, in this approach, the main object of study is the (whole) response time distribution of a single mental speed task and not just certain parameters of a limited class of distributions (or the relationship between different tasks). Because response time distributions play a central role, tasks are exclusively administered by computer, making the paper-and-pencil speed tasks used in the descriptive approach inappropriate. Second, one of the main aims of this approach is drawing inferences about cognitive architectures and their dynamics from the analysis of response time distributions. This aim is unique to the response time modeling approach because it entails more than just identifying and positioning new constructs in, for example, factor space. Instead, inferences aim at elucidating the interplay of certain hypothesized mental processes across time. Third, to achieve this aim, available mathematical-statistical models are rigorously implemented. Of note is the use of stochastic models to fit the dynamic nature of the variable(s) of interest. A final difference is that the response time modeling approach and its methods has not yet gained widespread attention in the individual-differences literature (for exceptions, see, e.g., Juhel, 1993; Vickers & Smith, 1986), though likely further advances in understanding mental speed will be predicated on the judicious use of this approach.[1]

Up until this point, we have used the term *mental speed* freely, without drawing any distinction between possible different meanings of this word. Indeed, numerous different concepts besides *mental speed* have been used in the literature to refer to constructs measured by any one of a relatively large class of tasks with low cognitive demands in which speed of response is primary. These include terms such as *speed of information processing, cognitive speed, processing speed, perceptual speed, clerical speed,* and *clerical-perceptual speed,* so it is no doubt judicious to clarify terminology. By the term *mental speed,* we mean to refer to the human ability to carry out mental processes, required for the solution of a cognitive task, at variable rates or increments of time. We reserve the term *cognitive speed* to refer to mental speed as studied within the explanatory approach, whereas we will use the term *psychometric speed* to refer to mental speed examined within the descriptive approach. The distinctions between the two approaches, although sometimes forced or artificial in the literature, as we shall show, do provide some principles for organizing a rather large body of knowledge around some core themes.

Cognitive Speed: Explaining Intelligence?

The explanatory approach has tended to focus on the relationship between measures derived from cognitively simple (i.e., trivially difficult) tasks and psychometric indicators of intelligence. Typically, these simple tasks have been based on theories within cognitive psychology; the hope is that they will provide theoretically tractable indices accounting for some or most of the variance in intelligence. Such tasks purportedly require only a small number of mental processes (or operations) to be carried out to arrive at the correct outcome and are not reliant on past-learned information (see, e.g., Carroll, 1993; Jensen, 1998).[2] These features have led to the term *elementary cognitive tasks* (*ECTs*) being coined for these classes of tasks. Often, however, it has turned out that the ECTs are more complex than initially believed (see Chapter 16, this volume). Yet given the hypothesized simplicity of ECTs, in which error rates tend to be low and randomly distributed across trials and individuals, time becomes the variable of interest. Various indices have been derived from the RT of these ECTs, including the slope and intercept of the regression of RT on some index of task difficulty (e.g., "bits" of information, array size), standard deviation of RT (SDRT), movement time (MT), decision time (DT), and difference scores between two conditions. However, it has proved to be the case that the indices postulated to measure a particular cognitive process (e.g., "rate of gain of information" indexed by the slope function of various RT tasks) have lower and less consistent correlations with psychometric measures than less theoretically tractable indices such as RT and SDRT (see, e.g., Deary, 2002; Lohman, 1994; Neubauer, 1997).

Much research has now been conducted investigating the relationship between various RT indices derived from ECTs and measures of cognitive ability, such that the existence of a moderate negative correlation has been firmly established. Some reviews of the relationship between RT and intelligence report that correlations range from –.30 to –.50, with multiple *R*s existing in the .70s for batteries of ECTs (see, e.g., Jensen, 1982; Vernon & Weese, 1993). However, these correlations are often corrected for unreliability or restriction in range, and the zero-order correlation is considerably lower. Importantly, one factor that has been shown to moderate the magnitude of the correlation of ECTs and intelligence is the complexity of the ECT (e.g., Larson, Merritt, & Williams, 1988). The finding is this: More complex ECTs (typically defined as those with longer reaction times; see, e.g., Neubauer, 1997) show higher correlations with measures of intelligence.[3] It is not our intention to provide an exhaustive review of research conducted within this framework (see, however, Jensen, 1982, 1987; Neubauer, 1997; Vernon, 1985), though later in the chapter, some of the main processes examined within this approach are described.

On the basis of the replicable relationship between RT and intelligence, it has been suggested that cognitive speed may be the fundamental process underlying individual differences in intelligence. For instance, Jensen (1987, p. 168) speculated that one might hypothesize that the general factor of a large, diverse battery of RT tasks is the same general factor, g, found in analyses of conventional psychometric tests. Many proponents of the explanatory approach (as well as researchers in other fields) commonly assume that the type(s) of processes underlying a wide range of timed measures contribute to a unitary construct of cognitive speed (e.g., Miller & Vernon, 1992; Neubauer, 1997; Neubauer & Bucik, 1996; Vernon & Jensen, 1984). Theoretical models have been proposed to account for the relationship, with the two main theories being Jensen's (e.g., 1982) "oscillator model" and Vernon's (e.g., 1987) "neural efficiency hypothesis," which both refer to a biological substrate to explain the correlations.

Despite the prospect of an explanatory model of intellectual functioning, there exist several criticisms of research conducted within this approach to mental speed (e.g., Stankov & Roberts, 1997). For example, Carroll (1993, p. 654) warns of specious claims that may be made if differential psychologists do not refer these measures of cognitive speed to specific strata of cognitive abilities. Carroll's prescription has so far been paid lip service; many researchers continue to place prominence on the correlation between ECTs and a general factor (i.e., psychometric *g*). Although the ECTs range from measures of simple reaction time to indices of long-term store (see, e.g., Roberts & Pallier, 2001), few researchers employ more than a single paradigm. Similarly, psychometric *g* is generally assessed by a single psychometric test (most often Raven's Progressive Matrices; see Juhel, 1991). Whether cognitive speed is general to a third-order (psychometric *g*), second-order, or primary ability factor (or factors) remains an open, empirical question with important conceptual implications.

It seems reasonable that Carroll's (1993) warning might also apply to the constructs that underlie ECTs (Stankov & Roberts, 1997). Thus, as we take up in more detail shortly, studies suggest that the nature of mental speed is multidimensional. Plausibly, the failure to take into account the complex structure of both cognitive abilities and constructs assessed by ECTs has hindered progress in the field. To illustrate the preceding point is an example from Roberts, Beh, and Stankov (1988). Using the card-sorting paradigm, Roberts et al. found a particularly high correlation between decision time and performance on Raven's Progressive Matrices. On the basis of additional analyses, Roberts et al. argued for the primacy of cognitive complexity to the general intelligence factor. However, when the card-sorting task was included in a more extensive battery of ECTs and psychometric measures, it was considered that (a) stimulus-response (S-R) compatibility mediated correlations with intelligence constructs, and (b) decision time was related only to fluid intelligence. Similarly, Roberts, Pallier, and Stankov (1996) demonstrated that a seemingly promising ECT (designed to provide an index of basic information-processing speed; see Lehrl & Fischer, 1990) was nothing but a proxy for Reading Speed, having little to do with the general intelligence factor.

Psychometric Speed: Describing Intelligence?

Ability Models Incorporating Speed. Although mental speed is typically considered as a unitary construct within the former approach, prominent theories of intelligence incorporate several mental speed factors within structural accounts of cognitive abilities. This framework provides a natural contrast to the explanatory approach. In this account, mental speed factors are considered as just one *part* of the realm of cognitive abilities, as opposed to a process potentially *fundamental to* the construct of intelligence.

As might be gathered from frequent references across the entire current volume, the two main hierarchical theories of intelligence are Horn and Cattell's theory of fluid and crystallized intelligence (Gf-Gc theory; see, e.g., Horn & Noll, 1994) and Carroll's (1993) three-stratum theory. Both models accommodate a number of broad factors encompassing such processes as reasoning (Gf), knowledge (Gc), memory (Gsm and Glr), and auditory (Ga) and visual (Gv) perception, as well as, at a lower level, the primary abilities that underlie these broad factors. Gf-Gc theory can be considered a truncated version of the three-stratum theory in that it does not incorporate a general factor (*g*) at the highest level, as Carroll's theory does (cf., however, Chapter 16, this volume).

Within Gf-Gc theory, two broad speed factors have also been identified: Gs or processing speed (generally measured by tasks of the primary factor clerical-perceptual speed), defined as being measured by "rapid scanning and responding in intellectually simple tasks (in which almost all people would get the right answer if the task were not highly speeded)" (Horn & Noll, 1994, p. 173), and Correct Decision Speed (CDS), "measured in quickness in providing answers in tasks that require one to think" (Horn & Noll, 1994, p. 173). Of these, it is Gs that has so far received the strongest empirical support (Horn, 1987), with some (albeit weak) evidence suggesting little relationship between CDS and Gs (Horn & Noll, 1994).

In consideration of factors that arose in data sets that he reanalyzed, Carroll (1993) also arrived at two broad (along with several narrow) speed factors (see Carroll, 1993, p. 626, Figure 15.1). The broad factors are designated Gs (broad cognitive speediness) and Gt (processing speed).[4] Carroll's first category of broad speed factors can be considered akin to Gs in Gf-Gc theory, in that the factors placed within this category tend to subsume first-order factors such as Perceptual Speed, Numerical Facility, and Speed of Test Taking. Carroll's second classification, Gt, comprises second-order factors that "tend to dominate various kinds of reaction time tasks such as the Hick paradigm" and "are chiefly *decision time* measures" (p. 618). Notably, the relationship between Gs and Gt is unclear in this exposition; classifications are based on examination of data sets that provided higher-order speed factors, with only five data sets yielding more than one such factor. However, what is clear is that a distinction is made between factors defined by RTs derived from ECTs, usually assessed using computers, and factors defined by speed tasks falling within the psychometric tradition, predominantly given by paper and pencil.

A Hierarchical Model of Mental Speed? It is worth noting that, until recently, no study had attempted to systematically measure the various mental speed constructs comprising Gf-Gc theory or Carroll's (1993) three-stratum model within one large, overarching study. Instead, the relationship between these factors of speed had been inferred. On this point there would appear considerable controversy. Compare thus the following widely disparate conceptual accounts:

> Some psychometricians have mistakenly believed that RT measures the same speed factor that is measured by highly speeded psychometric tests, such

> as clerical checking, number series comparisons. . . . The fact is that psychometric speed . . . is something entirely different from the speed of information processing measured by RT or IT [inspection time]. (Jensen, 1998, p. 224)

Horn (1985), by contrast, claims "Gs is . . . similar to the complex reaction times of Jensen's studies" (p. 283), and Carroll (1993) notes much similarity between processes involved in performing ECTs and those involved in performing various perceptual speed tasks (see, e.g., p. 489).

It is nonincidental to resolving this type of controversy that we opened this chapter with a quote from Carroll (1993) highlighting the possibility that speed measures might constitute a meaningful taxonomy. Needless to say, multivariate studies combining ECTs and more traditional psychometric measures of speed shed light on the interrelationships that different mental speed tasks share and, by doing so, provide insight into the structure of mental speed. The exposition turns now to consideration of such recent studies and the manner in which they are informing more complete taxonomic models of human cognitive abilities.

One distinct possibility is that mental speed tasks form as complex a hierarchy as level (i.e., accuracy) measures from psychometric tasks, with a general mental speed factor at the apex and broad factors of mental speed forming a second underlying tier (Stankov & Roberts, 1997). Support for this possibility comes from a study by Roberts and Stankov (1999), who aimed to determine the relationship that measures derived from ECTs share with cognitive abilities defined by level and speed, as well as to obtain information on the factor structure of mental speed itself. The study employed 21 psychometric marker tests of broad cognitive abilities (Gf, Gc, Gsm, Gv, and Ga), 12 measures of speed of test taking (from a subset of these psychometric tests), 4 measures of clerical-perceptual speed, and 11 ECTs. Variables derived from the ECTs included RT, decision time, and movement time.

Roberts and Stankov (1999) conducted several major analyses to shed light on the structure of this group of tests. Perhaps most enlightening are the results of a Schmid-Leiman transformation, which indicated 11 factors at the first order of analysis, 3 at the second order, and a general factor at the third order. The 11 first-order factors were interpreted as representing aspects of MT and DT from the ECTs, specific to certain tasks, as well as the psychometric speed factors of Tv/a and Tir (formed by speed of response on the tasks representing Gv and Ga, as well as inductive reasoning, respectively), Gs (or clerical-perceptual speed), and 2 other factors difficult to interpret.[5] The three second-order factors were clearly identifiable as general psychomotor speed, general decision speed, and general (psychometric) test-taking speed. Measures of MT, DT, and psychometric test-taking speed loaded on a third-order factor, interpreted as General Timed Performance (Gt), with loadings of sufficient magnitude to indicate this factor's generality.

On the basis of further analyses, Roberts and Stankov (1999) put forward a possible model of cognitive abilities that integrated their findings with Carroll's (1993) model of intelligence. The general speed factor was placed on the second stratum alongside the broad cognitive ability factors, and the five broad speed factors were placed on the first stratum, with the first-order speed factors placed on the same level as would be the tasks that define the primary mental abilities on Stratum I of Carroll's theory. Of note, too, is that of all the broad abilities sampled herein, only Gf evidenced consistent and moderate correlations with the various ECT measures. Similarly, the highest correlations between Gs and psychometric test-taking speed factors were with the Gf factor.

In another recent study, O'Connor and Burns (2003) investigated the structure of mental speed and the position of inspection time (IT) within such a structure. Evidence was found for a general mental speed factor overarching several group speed factors. The speed tasks in this study were three paper-and-pencil tests of Perceptual Speed (with accuracy as the dependent variable) and three ECTs: a choice reaction time (CRT) task with stimulus sets of two, four, and eight lights; an odd-man-out (OMO) task; and an IT task (median MT and DT were measured for the first two tasks). Two computerized psychometric tests (Swaps and Triplets, used elsewhere as Gf markers; see, e.g., Danthiir, Roberts, Pallier, & Stankov, 2001; Stankov, 2000) were also administered, having three "sections" in each task, with median correct decision speed from each section forming the measures taken from these tasks.

Both exploratory and confirmatory factor analyses were used to analyze the variables in this data set. The final model reported by the authors consisted of four factors at the first level and a higher-order general speed factor (designated Gs) at the second level of analysis. The four group factors identified were interpreted as Perceptual Speed (with loadings from the three marker tasks of this factor and a moderate loading from an aggregate of the Swaps measures), Visualization Speed (subsuming the Triplets variables, OMO DT, and IT), DT (defined by the CRT DT measures with a secondary loading from OMO DT), and MT (defined by all MT measures). This hierarchical model of speed shares similarities to that provided by Roberts and Stankov (1999), with the splitting of the psychometric test-taking speed factor into Perceptual and Visualization Speed the only notable anomaly.

Another study informing the hierarchical structure of mental speed was conducted by Neubauer and Bucik (1996). Although this study was not an attempt to delineate the structure of mental speed per se, but rather to investigate whether ECTs are important to all broad abilities underlying g, it is still of interest. Three paper-and-pencil versions of well-established ECTs were employed (i.e., Sternberg, Posner, and Coding Tasks) across the content domains of verbal, numerical, and figural. The BIS (Chapter 18, this volume) was employed to assess the intelligence domain, which provides measures of four operations: processing speed (measured by tasks similar to typical clerical-perceptual speed markers), memory, creativity, and reasoning.

Of interest, Neubauer and Bucik (1996) used a principal components analysis to determine the factor structure underlying the ECTs and extracted only one factor (termed *g-ECT*) on the basis that the first principal component accounted for 46.7% of the variance. In subsequent analyses reported, out of all the BIS components, *g*-ECT evidenced the strongest relationship with the processing speed component. The most compelling evidence for this relationship is seen in a structural equation model incorporating *g*-ECT with loadings from all ECT variables and four latent factors representing the operational facets of the BIS. The regression weight of *g*-ECT on the processing speed factor of the BIS was .86, .56 on processing capacity, .40 on memory, and .38 on creativity. Despite the very high correlation between mental speed derived from the ECTs and processing speed from the BIS, Neubauer and Bucik (1996) argued against equating the *g*-ECT with the BIS processing speed factor. However, given that the processing speed factor of the BIS is assessed by three subtests in three different content domains, it seems plausible that if different analyses were undertaken including all mental speed tasks in this battery, a general speed factor might have been found encompassing factors derived from both the ECTs and psychometric speed tasks.

Finally, of interest regarding the structural nature of variables derived from ECTs, and in contrast to the results of Neubauer and Bucik (1996), is a reanalysis of a data set obtained by Kranzler and Jensen (1991). In this instance, Carroll (1991) presents evidence suggesting that measures derived from different ECTs form separate factors. In the Kranzler and Jensen study, six ECTs were employed along with Raven's Advanced Progressive Matrices (RAPM) test and the Multidimensional Aptitude Battery (MAB). In a higher-order factor analysis using the Schmid-Leiman procedure, Carroll found evidence for two second-order and seven first-order factors. Five of the first-order factors were interpreted as representing processes specific to the ECTs (DT from OMO, DT from Search and Posner, DT from Hick and IT, MT from Posner, MT from Search, Hick, and OMO), and the other two were defined by measures from the psychometric tasks, identified with Gc and Gv. The first second-order factor was interpreted as a general factor, being defined by the decision speed and psychometric factors, and the second higher-order factor was defined by the MT factors.

Summary Statement. In contrast to the assumption evident within the explanatory approach—that mental speed is unitary—results from attempts to circumscribe the domain of the intellect indicate that mental speed is multidimensional in nature. However, due to the limited number of large-scale studies currently available that are directly aimed at measuring multiple indices of speed and the rather minimal consensus surrounding the factorial composition of speeded performance, the exact organization of mental speed constructs is anything but conclusive. Even so, the available evidence is suggestive of a considerably more complex structure than has generally been acknowledged in the literature. Indeed, when one looks both across differential psychology and outside this subdiscipline, one finds evidence for a number of constructs that might comprise a complete taxonomic model of mental speed. Arguably, a meaningful rapprochement between paradigms comprising the explanatory and descriptive approach to human intelligence, broadly defined, rests on attempts to provide full-blown structural models of mental speed. It is to a detailed exposition of the varieties of mental speed that might comprise such a model that discussion now turns.

Task Classes of Mental Speed

In the passages that follow, "major" mental speed concepts and various tasks contributing to their operationalization are described. This account is by no means exhaustive, though the concepts we have chosen to discuss have been studied in one or more published studies of human cognitive abilities (i.e., as either explanatory processes or part of the structure of human cognitive abilities). Where necessary, some of the controversies (and consensus) generated by particular attempts to model the psychological processes underlying tasks that serve to measure a particular construct are also introduced. It is our intention here to discuss constructs that might feasibly provide a comprehensive taxonomic model of mental speed, though, as will be reiterated throughout, current information concerning interrelations between these varieties of mental speed is piecemeal or scant at best.

Psychomotor Speed. The domain of psychomotor speed received great impetus, during the 1950s and on up through to the early 1980s, from Fleishman and colleagues' attempts to chart the domain of human movement (see, e.g., Fleishman, 1972; Fleishman & Quaintance, 1984; Peterson & Bownas, 1982). After a hiatus, researchers have recently refocused attention on the empirical status of MT (i.e., the speed associated with sensorimotor control of movement; see, e.g., Ackerman & Cianciolo, 1999, 2000), particularly in regards to its moderate negative relationship with intelligence (Roberts, 1997). The results from these studies are, however, at odds with earlier research, which suggested that there was no relationship between psychomotor processes and intellectual functioning. A plausible explanation for this discrepancy lies in the fact that contemporary research ironically fails to provide particularly rigorous measures of psychomotor processing. For example, in studies using a common experimental task—the Hick paradigm—measures of reaction time and MT are assessed within the same trial, with some MT "leaking into" a decisional stage (see, e.g., Smith, 1989). Elsewhere, further arguments are presented that suggest that contemporary psychometric investigations of MT have not been representative of psychomotor processes (Roberts, 1997).

Carroll (1993) gives this concept rather limited coverage, but there would appear at least three reasons why psychomotor speed might be reexamined. First, it is certainly not clear how concepts derived from other mental speed measures (with the possible exception of Decision Speed) relate to the various psychomotor abilities (e.g., Multilimb Coordination) that are defined under this framework (Roberts & Stankov, 1999). Second, emerging technologies afford more accurate and/or ecologically valid assessment of psychomotor responses. Finally, there appears at least one (as yet unpublished) study demonstrating incremental predictive validity over and above traditional forms of assessment, for some jobs, using some classes of psychomotor speed factors (P. C. Kyllonen, personal correspondence, 2003).

Inspection Time (IT). In this paradigm, the object is to determine the "threshold" amount of time that is required for an individual to detect a difference in two simple stimuli (e.g., a difference in the length of two vertical lines). The research examining IT in relation to intelligence is extensive (see Grudnik & Kranzler, 2001, for a recent meta-analysis), largely because of the minimal cognitive demands that this task places on the individual. In addition, IT has been founded on a particularly articulate cognitive theory (i.e., the so-called "accumulator model"; see Vickers, 1979). Curiously, IT's relation to other measures of mental speed is not well understood (i.e., the study conducted by O'Connor & Burns, 2003, is the first of its kind and merely suggestive), though clearly this might go some way toward resolving controversies evident in the literature (see, e.g., Stankov & Roberts, 1997). Similarly, to our knowledge, few studies have examined the factorial composition of IT tests, which may be administered in different modalities. However, evidence presented thus far may indicate an interesting anomaly relative to other measures of mental speed: IT measures presented tactually, aurally, and visually tend not to correlate too highly (Levy, 1992). The relationship that these paradigms share with measures of decision speed that may be presented tachistoscopically (over variable exposure durations) would also appear worthy of investigation (see Roberts & Stankov, 1999).

Decision Speed (DS). Arguably, the most extensively studied elementary cognitive processing construct throughout psychology is DS or CRT (see, e.g., Eysenck, 1987; Jensen, 1998). The task most widely employed in operationalizing this construct is the Hick task, in which typically, the participant responds by button-press to one light illuminated out of a set of one, two, four, or eight (see, e.g., Jensen, 1998, for a full description of the task). A demonstrated increase in DS to the number of stimuli to be processed is well documented and has become known as Hick's law (see, e.g., Roberts et al., 1988). The lawfulness of this effect, as well as the moderate correlation that tests of DS have with traditional forms of intelligence (i.e., *r*s around .30 to .40), seems to have been a major catalyst in the prominence of DS in the differential psychology literature. However, the linear function derived from DS is sensitive to a number of factors.

One such factor appears to be the relationship between stimuli and their associated responses, also known as stimulus-response compatibility (SRC) (e.g., Kornblum, 1994). SRC rests on the assumption that some codes are easier to process than others, and thus S-R codes vary in terms of compatibility. For example, responding to a visually presented stimulus of the word *LEFT,* with a left key-press, is highly compatible, whereas a right key-press would be incompatible. The limited evidence available suggests that SRC effects might moderate correlations between decision speed and intelligence (Neubauer, 1991; Roberts & Pallier, 2001; Roberts & Stankov, 1999). Because in each instance the studies finding these effects were more exploratory in nature, definitive tests of these propositions are so far lacking in the available psychological literature.

Odd-Man-Out Speed. In the odd-man-out task, initially employed by Frearson and Eysenck (1986), a "classic" eight-choice visual choice reaction time task is normally used, with one important modification. Instead of one light coming on, which the participant must extinguish, three lights are presented simultaneously. Two lights are closer together, and the participant's task is to move to the third light, which is clearly farther from the other two. There has been no satisfactory account of the processing involved in this paradigm, though correlations with external measures of intelligence are substantial (see, e.g., Burns & Nettlebeck, 2003; Diascro & Brody, 1994; Frearson & Eysenck, 1986). One way in which this type of task might be better understood is to examine it in relation to measures of other mental speed constructs; another is to provide more complete microstructural analyses of the type conducted by Beh, Roberts, and Prichard-Levy (1994; see also Roberts & Pallier, 2001).

Semantic Processing Speed. The purpose of cognitive tasks designed to assess this construct (based on the Posner paradigm; Posner & Mitchell, 1967) is to measure the time it takes to retrieve highly overlearned responses from long-term memory store. This is achieved by comparing performance on a simple discriminative task that involves a long-term memory component with performance on a task that requires virtually identical sensory discrimination (and response demands) but does not require access to long-term memory. A classic example of the former is whether two letters (e.g., *A a*) have the same name identity (NI condition; in the example, "yes"). An example of the latter uses the same stimuli but requires the individual to determine whether the items are physically identical (PI condition; in the example, "no"). Correlations between performance in the NI condition and intelligence are usually higher than between intelligence and performance in the PI condition. However, the measure in this class of tasks taken to represent the speed of retrieval from long-term memory—the difference score between the NI condition and the PI condition (NI – PI)—has met with equivocal success. In the 11 studies surveyed by Neubauer (1997) employing Posner-like tasks, the variable from these tasks having the highest mean zero-order correlation with psychometric intelligence (measured by various tests) was RT from the NI condition, rather than the NI – PI difference score. However, as noted for many of the other mental speed constructs, there have been no carefully designed studies that would place tasks defining semantic processing speed within a taxonomic model of mental speed.

Scanning Speed. Originating with Saul Sternberg (1966), in tasks measuring this process, a sequence of one or more items is presented, after which a single "probe" stimulus is presented. The individual's task is to decide (as rapidly as possible) whether the probe stimulus was present or absent in the initial series of stimuli. The time required increases linearly with set size, and the slope of the regression of RT on the set size is thought to reflect the speed of access to short-term memory. Similar to the difference score mentioned above, the slope measure has met with little success in terms of correlations with intelligence measures, with the mean RT correlations with intelligence, from 10 studies employing this measure, being –.29 compared to –.09 for the slope (Neubauer, 1997). Again, information on the relations that this cognitive task shares with other mental speed tasks is lacking.

Switching Attention Speed. Measures of this construct in differential psychology are scant. In a typical measure of attention switching, the individual is required to keep a simple rule in memory for odd-series items (e.g., count the number of vowels in a letter string). Another rule is given for even-series items (e.g., count the number of consonants in a letter string). The participant is required to switch between rules as quickly (and accurately) as possible. Süß and colleagues (Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2000) report moderate to high (.19 to .58) correlations between measures of task set switching and scale scores of both reasoning and *g,* derived from a test of the BIS model, and Kray and Lindenberger (2000) found similar results. Further empirical investigations are needed to determine the nature of the association between this type of task and other speed and level constructs.

Clerical-Perceptual Speed (CPS). Tests of CPS (also called Perceptual Speed) have been used in individual-differences research for some time. As early as 1938, Thurstone identified this as a primary mental ability. Much is known of the psychometric properties of this particular type of mental speed concept because it is often well represented in a range of multiple-aptitude and intelligence test batteries (e.g., Coding Speed and Number Operations from the ASVAB). In recent years, interest in CPS has gained in importance in cognitive psychology, largely due to the realization that these tests are closely tied to selective attention (Stankov, Roberts, & Spilsbury, 1994). For example, CPS has been found to be a major determinant of individual differences in skill acquisition (Ackerman, 1988; Ackerman & Cianciolo, 2000). French, Ekstrom, and Price (1963, p. 31) considered CPS to be a nonunitary factor, yet Carroll (1993, p. 346) stated that evidence for multiple kinds of this factor was meager. However, Ackerman and colleagues (Ackerman, Beier, & Boyle, 2002; Ackerman, & Cianciolo, 2000) have proposed a taxonomy of Perceptual Speed based on examining a considerably large number of tasks purportedly measuring this construct. Three of the four interrelated factors are (a) *PS–Pattern Recognition,* involving recognition of simple patterns; (b) *PS-Scanning,* involving scanning, comparison, and look-up processes; and (c) *PS-Memory,* interpreted as making substantial demands on working memory. The fourth factor proposed in their taxonomy is termed *PS-Complex,* but given the reliance on relatively complex cognitive processing in the two tasks used to assess this construct, the status of this factor as a "pure" Perceptual Speed factor is equivocal (see also Ackerman & Cianciolo, 2000). Despite these laudable efforts at examining the structure of CPS tasks, questions remain concerning the relationship of CPS (and its constituents) to other mental speed constructs.

Speed of Test Taking (STT). Measures of STT (i.e., the time taken to complete intelligence test items; similar to the CDS factor in Gf-Gc theory) have attracted little interest in the literature relative to abilities determined by number-correct scores. An assumption underlying STT is that it generalizes across primary mental abilities of level, but there is no compelling empirical evidence supporting this assertion. Few studies have been designed to examine the factor structure of speed of test taking per se, which may be worthy of further investigation given present evidence suggesting that several STT factors may exist (Roberts & Stankov, 1999; Vigneau, Blanchet, Loranger, & Pepin, 2002). However, it should be noted that although in all the other tasks mentioned, speed is explicitly a requirement, given that STT is derived from tasks that are typically more complex psychometric tasks, the focus is primarily on accuracy in these tasks. For this reason, STT can be considered in some respect fundamentally different from the other "types" of speed described herein.

Personal Tempo (PT). The study of mental speed has (virtually) ignored a potentially significant chronometric variable. Earlier in the past century, Spearman (1904, 1927) proposed that *mental speed* should be divided into *cognitive speed* (the speed at which a person performs specific cognitive processes) and *personal tempo* (the hypothesized speed at which a person tends to perform various daily activities). Studies of mental speed have focused almost entirely on the former. Another way in which PT could be conceptualized is as reflecting typical as opposed to maximal behavior. There are many attempts to assess intelligence as typical behavior (see, e.g., Ackerman, 1994; Wilhelm, Schulze, Schmiedek, & Süß, 2003), but few if any seem to address the typical speed of participants as assessed by self-reports. Accounts of PT tend to mention natural ways of walking and talking, doing routine jobs, and the like. Tests used to assess this construct include motor activities (e.g., tapping, clapping). It is usually assumed that people differ with respect to their natural speed of thinking as well (Roberts, 1997). Thus conceptualized, it is possible that any mental speed measure might depend partly on the natural speed at which a person operates. However, research into the factorial structure of measures of PT (Harrison, 1941; Mangan, 1959; Rimoldi, 1951) tends to be inconclusive, and Carroll (1993, p. 450) remarks that there is no clear evidence that the rate of performing cognitive tests is even correlated with personal tempo.

Further Varieties of Speed. In addition to the constructs covered above, a number of additional paradigms appear to measure important speed factors but have not been previously classified. These generally come from fields of enquiry less closely related to either differential or cognitive psychology. For example, both perception (e.g., McLeod & Ross, 1983) and human factors (e.g., Sidaway, Fairweather, Sekiya, & McNitt-Gray, 1996) researchers have assessed time to collision. Also of interest would be a range of speeded measures that emanate from neuropsychology, including specific tests such as trail making (which, with computerization and mathematical modeling of response patterns, might provide considerable refinements), as well as tests comprising full-scale batteries such as the MicroCog (e.g., Lopez, Sumerall, & Ryan, 2002). Equally interesting would be the assessment of the speed of particular psychophysiological functions, such as eye (the technology of which is improving), head (where the vestibular system is implicated and where individual differences have been found; see, e.g., Vibert et al., in press), and tongue movements (e.g., Murdoch & Goozee, 2003), all of which may provide important ancillary information to the measurement of many of the mental speed constructs discussed previously.

Summary Statement. The number of mental speed task classes covered by the preceding commentary is large. Notwithstanding, relatively few published studies have attempted to investigate the interrelations between more than a handful of these tasks, let alone charting an underlying taxonomy of mental speed (Roberts & Pallier, 2001). Consequently, there seems to be a need for detailed conceptual analysis, followed by large-scale empirical studies to uncover the major constructs of interest. This is no small point. Even the few studies conducted to unravel the varieties of mental speed have neither sampled all that widely across the task domain nor included particularly elaborate cognitive models of the underlying processes. Indeed, it is possible that several factors, isolated thus far, represent task or method factors rather than broader psychological constructs. Equally problematic, the stratum on which a given construct lies appears imprecisely defined (see Roberts & Stankov, 1999). In attempting to develop a hierarchical model of mental speed, these issues will require a series of carefully conducted multivariate investigations, possibly using missing data methods of the type discussed, for example, in Roberts et al. (2000).

The "Role" of Speed in Other Psychological Constructs

Although mental speed is explicitly a feature in cognitive ability measures that have speed as the dependent variable, it is also implicated in the administration of most other measurement paradigms used in intelligence (and cognitive) research as well. This can be illustrated by examining two prominent constructs in differential psychology: reasoning ability and working memory. It is our contention that the role of mental speed in each of these constructs is often understated.

Speed and Reasoning. In speeded tests, the person's performance is expressed as the number of correct solutions given within a certain time or as some average (or median) time per correct response. In nonspeed tests, time implicitly determines the score that a person achieves. In standard reasoning tests, for example, a time limit is usually applied in group administrations. The same is true for measures of fluency, crystallized intelligence, measures of short-term memory capacity, long-term memory retrieval, and other established cognitive ability constructs. The strictness of such time limits varies from test to test. We can use the same test with more or less strict time limits, and the rank order of participants need not be be the same on both measures.

If we decide to remove time constraints and give each participant as long as he or she needs to complete some predetermined test, time still plays some role, even though we might first try and ignore it. For example, if two participants both achieve the same score on this hypothetical test, most would agree that the person who was faster performed better. Although these considerations have been well known for some time, there is no easy solution with which to accord a fair assessment. Today, most nonspeeded tests are scored by the number of correct solutions. The time required is usually not expressed in the scores assigned to participants. If we restrict test time in such a way that a substantial number of participants are not able to work on all items within the time limit, additional factors might contribute to the score besides the underlying ability we are most interested in. Besides test-taking strategies and motivation, mental speed is one prominent candidate to explain the disturbed rank orders evident in a test administered under timed and untimed conditions. As a result, it can be expected that the correlation between mental speed and timed measures of reasoning ability will be higher than the correlation between mental speed and an untimed measure of reasoning ability. The difference between both correlations expresses the artifactual overestimation of the relation between mental speed and reasoning as assessed under timed conditions. Given that reasoning ability is measured within a time limit in most cases, the true correlation between both constructs might be considerably lower (Wilhelm & Schulze, 2002). It is important to derive bias-free estimates of the magnitude of *g* within a battery of intelligence tests (Chapter 16, this volume). Artifacts due to administration conditions certainly do not contribute to the credibility of intelligence research. Interestingly, though, whether time limits are important for all classes of abilities is also worthy of consideration in its own right. It is likely that for classes of tasks that are dependent on schooling or acculturation for high levels of performance, including many tests of knowledge, whether or not time limits are applied is often not so important, as long as they are not prohibitive.

Speed and Working Memory. Mental speed is also involved in the measurement of working memory functions. The relevance of mental speed in the assessment and explanation of working memory is at least twofold. First, inhibition, interference control, and supervision have been considered to be important determinants of working memory functioning. The tasks usually used to assess these functions are mostly scored by latency. Sometimes, these latencies are used as raw scores (Oberauer, Süß, Schulze, Wilhelm, & Wittmann, 2000), except for elimination of response times associated with erroneous reactions, response time outliers, and possible transformations to another metric. Indeed, these latencies mostly represent differences between some baseline condition and response times collected under an experimental manipulation. For task set switching, for example, trials immediately after switching the task set take considerably longer than tasks without such a preceding switch. This difference can be computed as the arithmetic difference between trials following each other (Rogers & Monsell, 1995). The sum of these differences reflects the overall cost of switching the particular task sets, assuming there are no differences in accuracies for both conditions. It is plausible to assume that trials with no switch as well as trials with switch reflect general speed as well as specific variance components. The implicit assumption is that the difference between both conditions takes away all the variance that does not reflect the effect of the experimental manipulation.

The general idea of using differences between reaction times is used within the mental speed framework, too, as seen in the Semantic Processing Speed tasks in which the difference between the name identity and physical identity conditions is used as an indicator of the speed of long-term memory retrieval. Whenever we use latencies, either as raw reaction times or derived through the computation of differences between experimental conditions, it is possible that the variables in question are substantially confounded with general mental speed. This bears mentioning because it is seldom considered as a rival account in some explanatory models of intelligent behavior.

The second manner in which mental speed is relevant to the assessment of working memory occurs because the administration of standard working memory capacity tasks (Engle, Tuholski, Laughlin, & Conway, 1999; Kyllonen, 1996; Oberauer et al., 2000) frequently relies on limited stimulus exposure times or combines a traditional short-term memory task with choice reaction time tasks in a dual-task paradigm (Oberauer, Süß, Wilhelm, & Wittmann, 2003). In widely used complex span measures (Engle et al., 1999; Kane et al., 2004), simple processing tasks are used to interfere with a second task, primarily the maintenance of some of the stimuli used for the processing task. Swifter processing can thus, as a consequence, reduce interference by reducing the time the "to-be-remembered" stimuli are exposed to interference or are subject to decay. In addition, all things being equal, faster participants have more opportunity to rehearse the to-be-remembered stimuli.

Consider, for example, a recent study by Ackerman et al. (2002). In this study, the authors argue that a major difference between working memory and a general factor of intelligence is that working memory is more strongly associated with a factor labeled *perceptual speed* than the general intelligence factor is associated with this factor. The working memory tasks used in this study were sampled from the literature and can be considered to be marker tasks for the measurement of individual differences in working memory. However, for all of the seven tasks used in this study, there was a time limit on stimulus exposure, a time limit for responses on a secondary task, or both. The Alpha span task (Oberauer et al., 2000), for example, proceeded by auditorily presenting common one-syllable words at a rate of one per second. After three to eight words were presented, participants were allowed 15 seconds to type in alphabetical order the first letter of each of the presented words. It is important to note that most working memory tasks used so far to great effect in attempting to derive explanatory models of fluid intelligence (see Chapter 4, this volume) apply such time limits. It is also important to note that in most cases, such time limits are pragmatically appropriate, and removing such time constraints would change the tasks that participants are asked to do. Nevertheless, the time constraints on stimulus exhibition and responding might introduce an artifactual relationship between mental speed and working memory. Consequently, the relationship between mental speed and working memory is likely to be overestimated in most studies. We strongly believe that more work elucidating such relationships is important to improve and possibly purify indicators of very crucial constructs.

CONCLUSIONS

Deary (2000) has argued that had it not been for several flawed studies conducted with early chronometric measures, it is entirely possible that instead of the types of intelligence tests commonly seen today, assessments might be those discussed in the above-mentioned passages. Certainly, speed of performance has many more tractable measurement properties than that provided by traditional intelligence tests, a point that has not gone unnoticed by both supporters, critics, and neutral observers of intelligence testing (see, e.g., Jensen, 1998; Kline, 1999; Kyllonen & Roberts, 2003). Ironically, however, whereas more than 400 studies have been devoted to uncovering the factorial structure of measures based on the types of intelligence tests seen today (see Chapter 14, this volume), in which accuracy is given prime importance, very few have paid speed of performance more than passing lip service, though with computers and other emerging technologies, this is bound to change (Chapter 19, this volume).

Having acknowledged this state of affairs as contemporary, research involving mental speed measures is likely to continue in the immediate future on a relatively nonintegrated path, unless some of the current prescriptions are followed. Beyond theoretical reasons for attempting to construct a hierarchy and taxonomic model of mental speed are obvious desiderata common to applied psychology. For example, it is an open empirical question whether cognitive aging, which has often been tied to "processing speed" or other speed-related concepts (see, e.g., Salthouse, 1991), might be better understood inside a multidimensional model of mental speed of the type proposed herein. Similarly, one might imagine improved prediction for clusters of jobs or educational interventions if mental speed is shown to be complex (see, e.g., Spearitt, 1996; cf. Schmidt & Hunter, 1998). In short, if there are indeed many varieties of mental speed, as is currently postulated, then relations that many tests of this generic construct share are poorly understood (see Roberts, Pallier, & Goff, 1999). The fact that many selection, clinical, or even educational applications have assumed that a given test is representative of clerical-perceptual, processing, coding, or some other global speed construct ignores the complex structure that these variables are likely to possess. The suggestion that a systematic program of research is required to develop a taxonomic model of mental speed constructs, several of which may serve as useful predictors in the selection context (and others not), clearly deserves empirical instantiation.

Beyond these very global, broad issues are many local issues that will also need to be addressed if models of mental speed are to prove themselves theoretically, empirically, and practically efficacious. For example, there remain important measurement issues associated with speed-accuracy trade-offs, though modeling techniques are becoming increasingly sophisticated to meet these challenges (e.g., Ratcliff, Van Zandt, & McKoon, 1999). The question of equivalence between the same tasks presented via different mediums also arises since this outcome affects operational decisions. Thus, a meta-analysis conducted by Mead and Drasgow (1993) found that differences in test medium affect the construct validity of mental speed tasks more than level (i.e., accuracy-based) tasks; the disattenuated cross-mode correlation was only .72 for speed tasks. Study 2 of Neubauer and Knorr (1998) assessed the equivalence of computerized and paper-and-pencil versions of two ECTs, deriving RT and derivative measures from each task. The correlations between the computerized and paper-and-pencil versions of each task were quite low (between .41 and .50), with the correlations between measures from tasks presented via the same medium being somewhat higher (between .49 and .67). There is thus evidence that the nature of the test medium affects the construct validity of mental speed tasks. A corollary of this point is that attempts to investigate the structure that mental speed tasks form will also need to take into account this fact. The structure that a variety of mental speed tasks evidence when all are presented on computers might differ from the structure that arises when tasks are presented in paper-and-pencil format; how substantially they differ, if at all, is an open empirical question that has yet to be investigated.

Another "local" emphasis that should be considered is the impact of different "scoring" algorithms, procedures, and/or methods. A comprehensive investigation of the relationship between the many different scores that are derived from computerized speed tasks would seem beneficial, particularly in regards to comparing results from studies that have used different methods. As mentioned here and elsewhere (e.g., Roberts & Pallier, 2001), the division of RT into separate decision and movement time components is considered problematic; some studies make the distinction, but others do not. Various methods of assessing central tendency in RTs exist, such as computing the median or the mean or using log-transformed data, and differences in studies exist in dealing with outliers (for an overview, see Van Zandt, 2002). Intraindividual variability measures (e.g., SDRT) have been reported to show higher correlations with intelligence than measures of central tendency (see, e.g., the reviews of Jensen, 1987, and Neubauer, 1997). The correlation between SD and the median of decision speed has also been noted to be so high as to imply redundancy of one index (Roberts & Pallier, 2001), and the two measures are typically experimentally dependent. Further investigation into each of these issues is undoubtedly useful.

Further investigation is also required to attempt to provide a satisfactory account of *why* such relationships between mental speed and intelligence exist. As mentioned previously, more "complex" ECTs (defined as having longer latency) correlate higher with intelligence. This definition of complexity, however, is conceptually devoid due to its ex post facto nature and is circular in its reasoning; that is, a task is considered complex if it takes longer to complete, and it takes longer to complete because it is complex. Stimulus-response compatibility appears one possible factor moderating the strength of the relationship between RT indices and intelligence, particularly Gf. Evidence exists that incompatible tasks evidence longer latencies (Kornblum, Hasbroucq, & Osman, 1990; Neubauer, 1991), and both Roberts and Stankov (1999) and Neubauer (1991) have found that, in general, decision speed from tasks manifesting low SRC exhibits higher correlations with Gf than those having high SRC. Ackerman et al. (2002) present similar results in regards to the relationship between Perceptual Speed tasks and working memory. Results are thus compatible with the contention that SRC may offer more theoretical insight into the notion of "complexity" in regards to mental speed tasks, given this construct's solid grounding in cognitive theory linked to the concepts of attention and automaticity (see, e.g., Ackerman et al., 2002), thereby providing one possible avenue through which to further our understanding of the relationship between mental speed and intelligence.

Much more work is obviously also needed in terms of understanding the construct of mental speed and its relation to other types of ability, as well as in regards to the role it plays in other constructs examined in the domain of cognitive abilities, such as reasoning ability and working memory. Research has recently been reported examining the interrelationship between speed, working memory, and reasoning (e.g., Conway, Cowan, Bunting, Therriault, & Minkoff, 2002); however, it could be argued that it is a logical requirement that first we need to understand the "thing" itself before we can fully understand its relationship to other constructs. Our understanding of the structure of mental speed is still in its infancy, yet evidence points to its multidimensional nature, as well as to differential relationships of subfactors of mental speed to other criteria (e.g., Ackerman & Cianciolo, 2000). It is hoped that this chapter will stimulate further research to provide a more definitive conclusion when the next edition of this volume is commissioned.

Notes

1. Readers interested in details of this approach might wish to consult Luce (1986), who gives an overview of models and methods for various types of tasks. Note that this rather rigorous approach has been implemented with some of the tasks to be introduced later in this chapter. However, most generally, a problem implementing it in individual-differences research is the large number of trials per participants required to obtain meaningful data.

2. If elementary cognitive tasks (ECTs) do rely on previously learned information, the information content is so overlearned that it would be familiar to everyone and is therefore assumed to not be responsible for much of the observed individual differences.

3. It is worth mentioning that these reaction imes (RTs) cannot be too high, however; the correlation between cognitive speed and intelligence tends to follow an inverted-U function as a function of time, with the peak close to 1,000 msec (beyond which it is thought that noncognitive processes begin to intrude on "pure" speeded performance; see Jensen, 1982).

4. Carroll (1993) also identifies a third category of second-order speed factors, designated Gp (or general psychomotor speed). However, due to this factor's minimal cognitive content, Carroll does not consider this strictly as a cognitive ability. Consequently, it is not included in his full-blown model.

5. Examples of some of the first-order factors representing movement time (MT) and decision time (DT) are as follows: Speed of Limb Movement, Multilimb Coordination, Decision Time to a Light-Key Stimulus-Response (S-R) Code, and Decision Time to a Pictorial/Symbolic-Motor S-R Code. Notably, the first-order MT factors correspond to findings in the psychomotor literature, whereas the first-order DT factors appear to be defined by the nature of S-R mappings that must be engaged in to successfully complete these types of tasks.

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