Chapter 7

g and Cognitive Elements of Information Processing: An Agnostic View

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PROLOGUE

Searching for cognitive elements of human mental ability differences, and focusing that search on *g*, has a venerable record in our field of inquiry. The search, which Hunt (1980) compared with the search for the Holy Grail, is an interesting one to document, partly because researchers' opinions on the same data can be diametrically opposed. In 1904 Spearman found small to medium-sized correlations between mental ability estimates and measures of sensory discrimination. He speculated that, after correcting for unreliability in the measures, the correlation between discrimination and mental ability was near to 1.0, and that discrimination was the psychological basis of human mental ability differences. (Although he withdrew the comment a few years later [Burt, 1909–1910], he repeated it in his magnum opus [Spearman, 1927]). In 1909 Thorndike, Lay, and Dean found very similar correlations to those of Spearman when they examined sensory discrimination and higher level mental abilities, and they remarked that it was tenable to conclude that discrimination and mental ability differences were unrelated (a correlation = 0.0). Such is the violence that prior theory may wreak on congruent data.

Introduction

This author sits enthusiastically as a spectre at this feast of an edited volume. The structure first proposed for the book, that we authors be broadly pro- or anti-*g*, had the same principal attraction as a jousting contest between knights in "olde" England: namely, that the mob loves a good scrap, and the more blood spilt the better. However, academic debates also share the same demerits as the chivalric contests: They tend to emphasize disagreement over agreement; and they obscure the good qualities of the two sides, with only one seen as a winner. Going back to the prologue, it would have been much more memorable to watch Spearman and Thorndike aim big lances at each other than to hear a timid exposition on how one might further investigate the small-to-medium effect size of the association between sensation and intellect. But the present chapter exhorts the reader to eschew entertainment value and to prize those replicated, if at times small, effect sizes and to question psychologists' theories about how correlations have come about. In a research topic where "theory" at times comes close to meaning "poorly substantiated prejudice" it is helpful to keep a close eye on the empirical data and to appreciate its strengths and weaknesses. Therefore, in what follows, I have consciously avoided partial subscription to *g* or non-*g* theories of mental ability differences. I have essayed a disinterested weighing-up of the importance and relevance of the finding of general psychometric ability variance in the search for cognitive contributions to mental ability differences.

First, the broad "lie of the land" (see Neisser et al., 1996). There are three main types of mental ability research: psychometric studies, predictive validity research, and reductionistic validity research. This chapter concentrates on the last of these. In service to the particular theme of this book one may address *g* within each type of research, but also emphasize that there is more to all three types of mental ability research than *g*.

With regard to psychometric studies of human mental abilities there is much that is known. When a large sample of the population, at any age from childhood to old age, is administered a diverse battery of mental tests the covariance structure forms a hierarchy. At the peak of the hierarchy there is a general factor, typically accounting for about 40% to 50% of the test score variance. Below this, there are correlated group factors of ability. These do not attract full agreement between studies, reflecting the different salads of tests' contents in different batteries. At a still lower level in the hierarchy there are specific abilities, which form correlated but separable aspects of the group factors. This hierarchical structure is found in single large experiments (Gustafsson, 1984) and in surveys of large numbers of psychometric studies, including many classic databases, some of which originally were thought not to contain *g* (Carroll, 1993). With regard to predictive validity studies, mental ability differences are significant predictors of educational, occupational, and social outcomes, with effects sizes that are typically moderate to large (Gottfredson, 1997).

For researchers interested in reductionistic validity studies the latter findings suggest that the mental tests whose information-processing origins are being sought have at least some practical importance. The psychometric studies suggest that there might be different targets for cognitive or broader information processing studies: general variance, and group and specific factor variance (see Roberts & Stankov, 1999, for strong advocacy of this approach). On the other hand, people conducting reductionistic validity studies need to be aware of the limitations of psychometric studies. Any human mental abilities not included in typical psychometric tests might need additional information-processing accounts (Gardner, 1983; Sternberg, 1999). And it must be recalled that the hierarchical structure of the covariance of ability test scores exists as a finding that is not necessarily isomorphic with anything in people's heads; the three-level hierarchy is a taxonomy of tests, not of human's mental structures (not necessarily, anyway). These, therefore, are the first three limitations facing information-processing research into human mental ability differences: that one must be aware of what ability level is being "explained," that the psychometric enterprise might leave some abilities untouched, and that psychometric structures are not necessarily reflected in the brains of humans. In each of these limitations is an explicit agreement that there is more to mental life, and its cognitive underpinnings, than *g*.

Information-processing constructs, be they more cognitive or biological in their level of description, are meant to index important aspects of brain processing; there is no guarantee that psychometric structures do any such thing. But, the fourth warning for the would-be reductionist is even more gloomy; that there might be no current cognitive or biological model of mind from which to cherry-pick information processing parameters, the interindividual variance which might account for variance in mental test scores. That is, despite Spearman's (1923) search for a "mental cytology" that would provide a parameterization of mind, despite the cognitive revolution promising a catalogue of "mental components" (Sternberg, 1978), "microscopes of mind" (Massaro, 1993), and ways to "parse cognition" (Holzman, 1994), despite psychophysics promising some "benchmark tests" (Vickers & Smith, 1986) of human mental operations, and despite elaborate artificial intelligence models of 'general intelligence' (Laird, Newell, & Rosenbloom, 1987) we are still a long way off Galton's (1890) aim of being able to drive a few shafts at critical points in the mind to gauge its working efficiency.

To recap on the remit for this chapter, in which the author was asked to reflect on the importance that *g* has in cognitive accounts of mind, there are three things that need addressing after agreeing that *g* does at least emerge from analyses of psychometric test score batteries. The other matters to be considered are: What cognitive theories and variables have been used to try to account for psychometric mental ability differences?; what is the place of *g* versus more specific abilities in this search?; and what validity do the cognitive variables and theories have, given that they do provide variables that correlate with psychometric *g*?

In terms of cognitive candidates to account for human ability differences, it is worth discerning three broad approaches. Cognitive variables have emerged at three different levels of reduction, which shall be called psychometric, cognitive–experimental, and psychophysical.

PSYCHOMETRIC-LEVEL COGNITIVE CONSTRUCTS AND *g*

Sometimes psychometricians appear to get ideas beyond their stations. They act as if their tweakings of mental tests' contents are facets of human cognitive assemblies and functions. It's not impossible that the lineaments of mind might be read in a pattern of test performances, just unlikely. However, in the meantime, such psychometricians have come up with some ingenious ways to calibrate the grades of difficulty within mental tests. A good early example is provided by Furneaux (1952) who manipulated the content of mental tests and divined people's reactions to them and saw among people differences in mental speed, persistence, and error checking. Here, too, was the possibility of a disunitarian *g*, because these three mental characteristics combined to give people's ability test scores. Furneaux's ideas, although championed by Eysenck (1967), never were rendered in full detail and failed widely to influence psychologists. But the idea that the nature of ability test performance, not least *g*, might be revealed through dissecting mental tests themselves did catch on. Since then, although the idea that *g* might comprise unrelated or at least separable cognitive components has been acceptable even to its strongest protagonists (Jensen, 1998a), others have asserted that a single process might underlie *g* (Brand, 1996).

One research program that promised to change the face of intelligence research to a more cognitive complexion was Sternberg's (1977a, 1997b). His vision was of factors of mental ability (including *g*) being replaced by mental components (Sternberg, 1979). Mental components were the consecutively turning cogs, or serial mincing machines, that took in mental test items at one end and produced answers at the other. The first assault of "componentman" on "factorman" (Sternberg, 1979) was on analogical reasoning, although he subsequently took on classification and series continuation reasoning (Sternberg & Gardner, 1983). For someone who was avowedly cognitive, Sternberg was historically very well aware of the history of the psychometric disputes surrounding *g* and he chose to examine analogical reasoning precisely because it was viewed by landmark psychometricians as close to the heart of what *g*, cognitively, was. And Sternberg's scheme of mental components and their activities stayed close to the ideas of *g*'s inventor–discoverer (Spearman, 1904, 1923). According to Sternberg, analogical reasoning items were solved by a series of operations—mental components—called encoding, inferring, mapping, application (and responding, justification, etc., which appeared later, on occasion). Take the analogical reasoning item,

fish is to swim as bird is to [robin, fins, fly, wing, feather]

Progressing beyond the perhaps-true-in-some-sense-but-ultimately-unhelpful statement that people who did well on such tests had a lot of *g*, which leaves the problem of unpacking *g* untouched, Sternberg (1977a, 1997b) described the cognitive components involved in such reasoning. The analogy's items were "encoded." A relation was "inferred" between the first and second items. Mapping was performed between the first and third items. The relation between items 1 and 2 was then "applied" to item 3 and the correct answer (fly) was chosen from the answer options. These cognitive elements or components were akin to Spearman's (1923) rationalist–philosophical cognitive account of mental activity. Indeed, Spearman's lesser known book which produced this cognitive architecture has been dubbed the first book on cognitive psychology (Gustafsson, 1992). Spearman's economical cognitive architecture, designed to account for much of human thinking, contained only three components: the apprehension of experience, the eduction of relations, and the eduction of correlates. Apply these to Sternberg's analogy items. The apprehension of experience might equate to encoding items. The eduction of relations means finding general rules or relations from more than one instance: thus, the higher order, relational concept of "mode of movement" emerges from fish and swims. Taking up the third term in the analogy—bird—we can then apply Spearman's third principle. This is the eduction of correlates, the mental activity that takes an example and a relational rule and generates an outcome. Applying mode of movement to bird gives fly.

Sternberg (1977a, 1977b) did more than merely revive and expand Spearman's principles of cognition. He invented a method for discovering the amount of time it took for each component to operate within an individual. Thus, if analogical reasoning was close to what psychometricians thought of as a *g*-loaded test, here was a multicomponent account and, to boot, a way of measuring people's differences in each component. If the scheme works, *g* is relegated to a kind of arithmetical summary of components' efficiencies. The method was called "partial cueing" and its essence was in allowing subjects to study one, two, or three analogy terms prior to viewing the whole item and responding as fast as possible. From a series of simultaneous equations and a regression method, subjects' efficiencies for each of the components could be ascertained.

But *g* didn't fracture along the lines drawn by the Sternbergian components. The enterprise lost steam along the way and there is little current interest in the components. The proper attempts were made to show that the same components could be extracted from different tasks and that different components were distinct from each other. However, parameters of the *same* components from different tasks tended to correlate at about 0.3 and different components' parameters tended to correlate at about 0.2 (Sternberg & Gardner, 1983). Given that the samples were typically small and often involved students, these were not significantly different, leaving the possibility of a general factor permeating the components' efficiencies. The same components did not always emerge from the tasks, additional components were introduced seemingly on an ad hoc basis, and at times conglomerate components—like a *reasoning* component—were introduced that seemed almost to admit reductionistic failure (Sternberg & Gardner, 1983). It became clear that the monophrenic strictures of the componential model did not fit the pluralistic mental wanderings of different people as they thought their various ways through reasoning problems (Alderton, Goldman, & Pellegrino, 1985). For example, high-ability people seemed to have different task structures than lower ability people, and they were differently advantaged and disadvantaged by viewing answer alternatives. Although there were criticisms that the components were self-evident and did not need empirical studies to validate them, the truth was precisely the opposite (Kline, 1991). There was insufficient evidence that the components were anything other than arbitrary choppings-up of the time taken to perform highly *g*-loaded tasks. To establish the validity of mental components required a research program that demonstrated the existence of the components as brain processes independent of the psychometric tasks from which they were extracted. That didn't happen and the components have remained as clever slices of test scores rather than validated mechanisms of mind.

Three widely cited research programs that followed Sternberg's pathbreaking work also peered within psychometric test items for the nature of individual differences in mental functions, with potentially strong implications for *g*.

Raven's Progressive Matrices (RPM; Raven, 1938) is a psychometric test constructed according to Spearman's (1923) cognitive principles of the eductions of relations and correlates, principles that Spearman deduced from armchair musing rather than empirical investigation. Scores on the RPM tend to load very highly on *g* (Marshalek, Lohman, & Snow, 1983) and understanding the constituents of differences in RPM performance might unpack some of the general factor's variance. Using subjects' verbalizations and their eye movements while solving RPM items, an explicit series of rule-finding and other imputed mental functions was written into two computer programs, which were thereafter average and good, respectively, at solving RPM items (Carpenter, Just, & Shell, 1990). In general terms the better computer program, reflecting the higher scoring subjects' performances on the RPM, found more correct rules in the items and could concurrently handle more transformations demanded by the rules at any one time. This research seemed to indicate that RPM performance, and *g* to the extent that it is captured in the RPM test, was something to do with working memory and goal management strategies. According to Carpenter et al.,

> One of the main distinctions between higher scoring subjects and lower scoring subjects was the ability of the better subjects to successfully generate and manage their problem-solving goals in working memory. (p. 428)
>
> Thus, what one intelligence test measures, according to the current theory, is the common ability to decompose problems into manageable segments and iterate through them, the differential ability to manage the hierarchy of goals and subgoals generated by this problem decomposition, and the differential ability to form higher level abstractions. (p. 429)

It is shown later that working memory and *g* must conceptually be brought closer together; they are closely linked concepts yet their researchers work in almost nonoverlapping agendas. In addition, the management of mental goals is also some researchers' favored cognitive account of *g*. For example, it was suggested that the location of *g* differences lies in the frontal lobes and that the chief psychological function of this area is goal management (Duncan, Emslie, & Williams, 1996). The suggestion comes from research based on a cognitive test involving a "second side instruction." In this test the subject reads a column of numbers, ignoring letters interspersed with the numbers within the column, and also ignores an adjacent column of letters and numbers. Every so often in this busy mental stream of thinking and responding there comes a second side instruction: a plus or minus sign tells the subject to stick with one side or switch to the other. The finding was that people with lower ability and people with frontal lobe damage were less able to implement the second side instruction, even when they saw and understood it. The authors urged that *g* be viewed as a cognitive property of frontal lobe functioning.

Back to the computer implementation of RPM (and *g*) performance (Carpenter et al., 1990). What did such an elaborate exercise achieve? At best it might have revealed aspects of mental performance that have validity in a mental architecture, reducing or dissolving *g* into more brain-anchored cognitive mechanisms. That doesn't seem likely, for in the published account of the research there is a clear trail from the RPM items to the computer programs that does not seem to fractionate the mind. The principles used to construct the successful programs appear rather too similar to the original principles that Raven used (which he got from Spearman) when he constructed the test. And it is likely that subjects' verbal reports and eye movements had some isomorphism with the tests' principles of construction. Although the investigators came up with some imputed mental functions that were more or less efficient in solving RPM items in differently abled subjects, they did this largely by commenting on what, subjectively, is required to think about in order to solve RPM items. The real opportunity for reduction was not this type of rationalism, which might in fact represent more armchair musing along the lines of Spearman's original principles of cognition, but lay, instead, in the details of the computer programs. The selected alterations in the program between the high and the low-ability subjects, had the computer program details been tied to a theory of cognitive architecture, might have provided hypotheses about the brain differences between higher and average ability subjects. But no such parallels seem to have been drawn or intended, and the qualitative differences between the computer programs, which involved one program being unable to induce a given rule and one program having elements that the other lacked, seem unlikely to reflect the quantitative brain differences among human subjects.

A successor to the Sternberg (1977a, 1977b) approach of mental components has been to construct mental tests with a manipulable aspect of content (perhaps thereby indexing a cognitive component) whose difficulty levels are explicitly graded to put a putative mental function under increasing pressure. Thus working memory has been manipulated in psychometric mental tasks to allow the extraction of a latent component that indexes the strength of different subjects' working memory efficiency (Embretson, 1995). In this task a second latent trait was extracted—it provided a sump for the other sources of individual difference—and was called *general control processes*. Perhaps not *g*, then, as a focus for research into mental ability differences, but these two more cognitive-psychology friendly components? They certainly performed well in accounting for the covariance among a battery of different mental tests (Fig. 7.1). But the author recognized explicitly that the success of these components relies not just on their psychometric performance but on their being part of a strong prior theory of cognitive architecture and function; just what is presently lacking.

Working memory differences take center stage as an alternative, more cognitively oriented, construct to *g* in another cognitive model of mental performance (Kyllonen, 1996a, 1996b; Kyllonen & Christal, 1990). This model is founded on a simple mental architecture and, although it con-

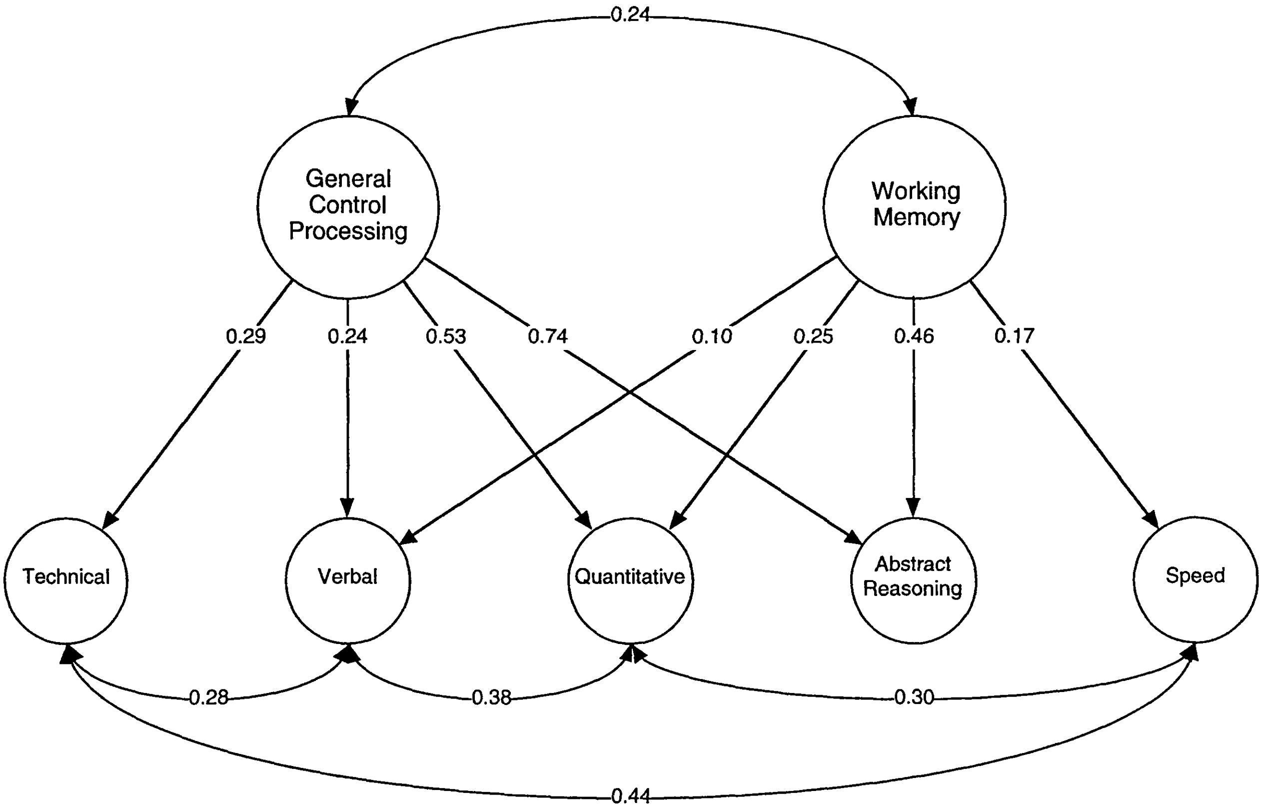

FIG. 7.1. Structural model showing that latent components of 'working memory' and 'general control processing' mediate the associations between factors from the ASVAB battery and scores on Embretson's abstract reasoning task. This figure was redrawn from Embretson (1995).

tains boxes and processes that most psychologists would recognize, it does not describe a modern, accepted mental architecture (Fig. 7.2). The model has been used to formulate a cognitive assessment battery which, rather than possessing a *g* factor, delivers scores on four factors: working memory, general knowledge, processing speed, and reasoning. Various large samples of armed forces applicants and recruits have been tested on the battery and other tests and the general result is that reasoning by analogy and other means (mental effort assessed by tests that are reckoned to be close to *g*) has a very high (> 0.8) correlation with a latent trait from the working memory subtests in the battery derived from the four sources model (Fig. 7.3). This has the effect of emphasizing the importance of *g* and at the same time diverting attention away from it, for it says that working memory might be the more useful, tractable cognitive construct to explore in asking about the meaning of the general variance in mental tests. Scrutiny then attaches to the tasks used to assess working memory: They turn out to be very psychometric-looking tests. Indeed some of the working memory tests are called *reasoning* tests. The model does show two separable constructs from two sets of psychometric tests (the set that is supposed to be a standard psychometric reasoning battery and the set that is supposed to assess working memory), but the nature of the tests does not make one more cognitively tractable looking than the other. Naming one factor *working memory* and the other *reasoning* does not confer causal precedence, nor does it securely attach the label to validated brain processing mechanisms, and the two are almost too closely correlated (the *r* value of-

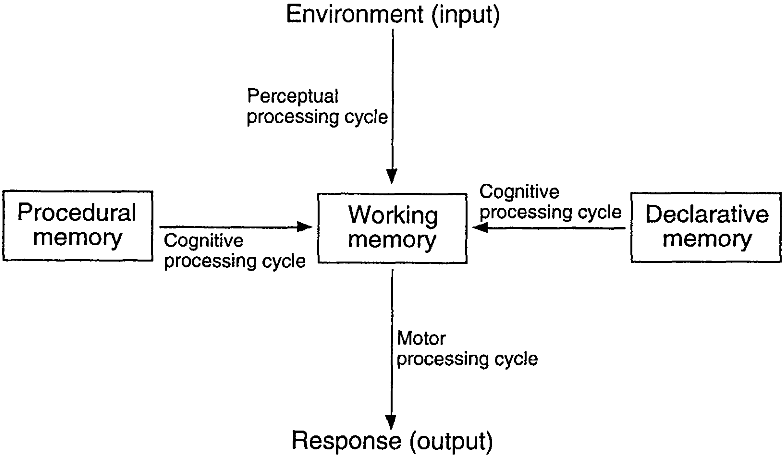

FIG. 7.2. The cognitive architecture used by Kyllonen and Christal to examine associations between working memory and psychometric intelligence. This figure was redrawn from Kyllonen and Christal (1990).

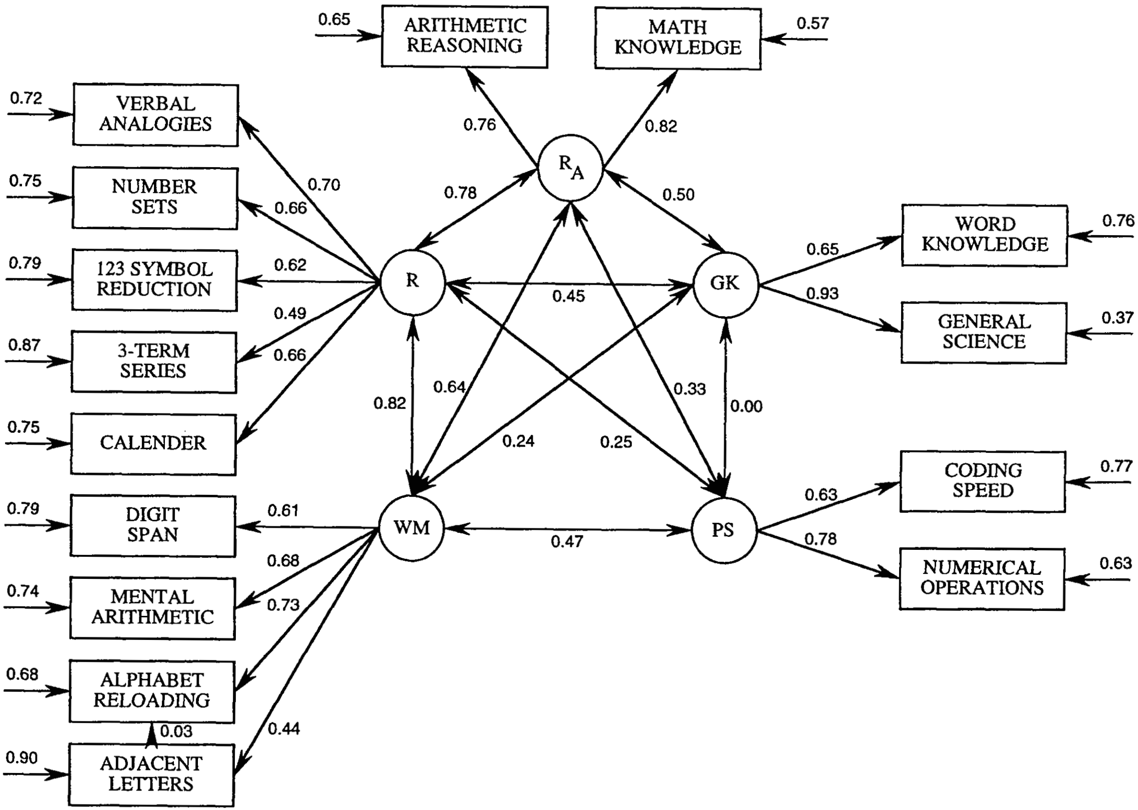

FIG. 7.3. Structural model showing the associations among latent variables of reasoning (R), working memory (WM), processing speed (PS), general knowledge (GK) and ASVAB reasoning R_A. Rectangles represent manifest variables (test scores). This figure was redrawn from Kyllonen and Christal (1990).

ten approaches unity). These concerns raise the question of whether this is just another discovery of *g* or whether it truly begins to reveal *g*'s essence(s). Indeed, an investigation of the general factor extracted from this four-sources cognitive battery and a general factor from a standard psychometric test battery resulted in a correlation of 0.994 (Stauffer, Ree, & Carretta, 1996; Fig. 7.4), suggesting pleonasm rather than explanation. The four-sources cognitive battery, then, clearly emphasises the importance of *g*, but its contents are not sufficiently theoretically tractable to inspire confidence that any distance down the road toward understanding *g* has been traveled. Perhaps the most positive aspect of this cognitive-level research has been to signal the fact that research on working memory, with its wealth of data from neuropsychology, cognitive psychology, and functional brain scanning, may be brought to bear on our thinking about the nature of *g*: no matter what we call them, two constructs as closely empirically related as working memory and *g* have a promising future as a couple (Baddeley, 1992a, 1992b; Baddeley & Gathercole, 1999). Engle, Tuholski, Laughlin, and Conway (1999) claimed "very strong evidence" (p. 328) for the association between working memory and fluid general intelligence.

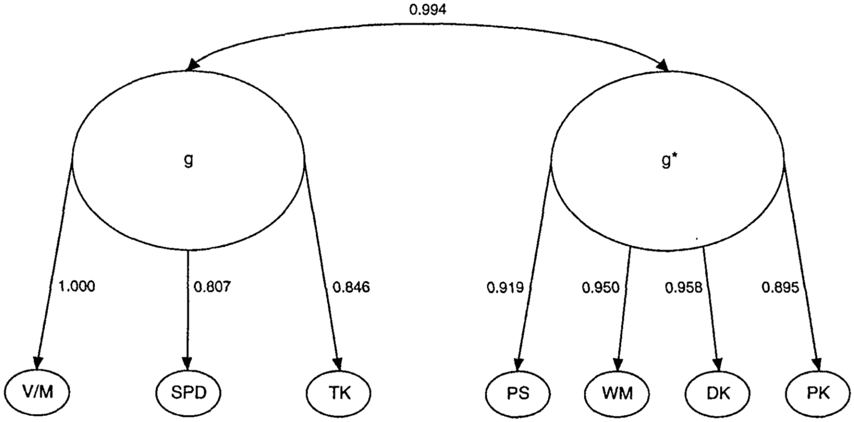

FIG. 7.4. Structural model with maximum likelihood estimates showing the association between general factors obtained from a set of paper-and-pencil tests, the ASVAB and computerised cognitive components measures, the CAM. The first order factors of the ASVAB are verbal/mathematical (V/M), clerical speed (SPD), and technical knowledge (TK). The first order factors for the CAM are processing speed (PS), working memory (WM), declarative knowledge (DK), and procedural knowledge (PK). Note the almost perfect correlation between the two general factors and the very high loadings of the first order factors on the respective general factors. This figure was redrawn from Stauffer, Ree, and Carretta (1996).

COGNITIVE-EXPERIMENTAL-LEVEL COGNITIVE CONSTRUCTS AND *g*

Sternberg's building a componential model of mental performance may be seen on the backdrop of a wider change in psychology in the 1970s (Deary [1997] reviewed this movement). With the rise of cognitive psychology came renewed impetus toward understanding the processes that linked to give the melodies of human thought. Really, the search was on for cognitive-level constructs that would provide what some called "microscopes of mind" or a "parsing" of human thought. With differential psychologists' realizing that factor models of ability might always be limited to describing and construing aspects of the tests that gave rise to them, many visited cognitive models to select those constructs that might account for some of the variance in mental test score differences.

In advance of the empirical evidence there is no reason to emphasize *g* over other factors in this approach. Isolable cognitive elements might relate solely or more strongly to *g* or to other ability factors. Early on in the cognitive–differential communion aimed at intelligence differences Hunt and MacLeod (1978) saw that, if there were many independent cognitive operations that linked to different psychometric abiltities, then *g* could lose much of its interest and importance. Although the constructs of working memory and goal management are current cognitive favorites to account for mental ability differences, there are three cognitive constructs that attracted attention during the years since the cognitive revolution. First, there was the slope parameter from the Hick (1952) reaction time task, which was hypothesised to index a person's "rate of gain of information." Second, there was the slope parameter from the Sternberg (1966) memory scanning task which was reckoned to measure the speed of scanning of items in short-term memory. Third, there was the difference between name-identity and physical-identity reaction times in the Posner reaction time task (Posner & Mitchell, 1967), which some researchers thought might measure the time to consult an item in long-term memory. Therefore, individual differences researchers had the opportunity to measure differences in people's ability to absorb environmental information of different levels of complexity and differences in the efficiency with which they could consult their long and short-term memory stores. Might these apparently elementary parameters of the mind relate to higher level cognitive performance differences, and perhaps to *g*?

An important distinction is between the aforementioned constructs and the tasks from which they arise. In each case, as the cognitive procedures became adopted by individual differences researchers, one can discern a progressive pattern of cognitive obfuscation. First, interest from differential psychologists focused on a single parameter that could be shelled out from the subject's performance on the cognitive task. Thus the first attachment is to some theoretically powerful element within the overall task. This is often a slope parameter; that is, the cognitive variable of interest is the subject's performance on one aspect of the task relative to another. One can easily see how such an enterprise threatened to water down *g*'s standing in mental ability research. If particular mental processes/parameters/components/mechanisms could be measured, there might turn out to be many of them, all related to different psychometric abilities. A modular story might thereby fit the cognitive and the psychometric data. An early success in this mode occurred with verbal ability and its relation to performance in reaction time tasks related to verbal materials (Hunt, Lunneborg, & Lewis, 1975). But this processes of filleting out key cognitive processes, usually slope parameters derived from reaction times, from the fat and gristle of overall reaction times and indigestible intercepts ran into problems and has failed to deliver an account of *g* or any other cognitive factor. Early on it was emphasized that those wishing to weld cognitive and differential approaches to ability differences should consider the implications of drifting from the purity of the derived cognitive parameters to the adoption of overall reaction times in cognitive tasks (Hunt & MacLeod, 1978). The latter outcomes owed little to cognitive models of task performance and, if they did prove to have significant correlations with ability test scores, they would not be understood in cognitive terms, unlike the slope parameters. What happened, though, was that so-far cognitively intractable variables such as overall reaction times and intraindividual variability in reaction times proved to be better correlates of mental ability test scores than did the theoretically more interesting slope parameters. This may be seen in the review of the Hick reaction time procedure and mental test scores that was carried out by Jensen (1987, see also 1998a) and in the review of the Hick, Sternberg, and Posner reaction time tasks and cognitive ability test scores carried out by Neubauer (1997). The slope of the Hick reaction time procedure has no special correlation with psychometric ability test scores and is usually outperformed by more mundane measures such as overall reaction time and the intraindividual variability of reaction time. Correlations between individual reaction time parameters and psychometric ability test scores tend to have small to medium effect sizes. Now, the correlation between these aspects of reaction times and mental test scores is surprising and not without considerable interest, but it betokens a redirection of interest, because the reason that differential psychologists adopted the task in the first place was that the slope parameter might be a human information-processing limitation. Although there has been less published research, a similar story emerges for the Sternberg memory scanning task and the Posner letter matching task. In both cases there are significant and modest correlations with mental ability test scores but they tend not to be with the theoretically attractive cognitive components assessed in the reaction time slopes; rather it is the intercept or overall reaction times and/or their intraindividual variabilities that correlate with psychometric test scores (Neubauer, 1997). Again, this is of interest in itself. Reaction times are a different type of task to psychometric tests and it is reasonable to suggest that reaction times might prove more amenable to understanding than mental test scores. Therefore, for the smallish part of mental test variance that they represent, reaction times might offer some information about what distinguished the less from the more able performers on mental ability tests.

But will reaction times tell us about *g* or more specific factors of mental ability? Although some suggest that reaction time tasks form their own specific factors in the hierarchical structure of mental abilities (Carroll, 1993; Roberts & Stankov, 1999; Stankov & Roberts, 1997) there is evidence suggesting that they have a place within an account of *g*. A large general factor, often between 50% to 60% of the variance, may be extracted from a battery of reaction time tasks' variables, such as those from the Hick, Sternberg, and Posner procedures (Neubauer, Spinath, Riemann, Borkenau, & Angleitner, 2000; Vernon, 1983). Some find that much of the association between a battery of mental tests and reaction time tests can be attributed to general factors in both (Jensen, 1998a, p. 235; Vernon, 1983; see also Neubauer & Knorr, 1998). However, in a large sample of adults that may be noted for its unusual representativeness (many other studies have used university students), reaction time variables had a stronger association with a fluid as opposed to a crystallized *g* factor (Neubauer et al., 2000; although one must recall that Gustafsson [1984] found that the second stratum Gf loaded perfectly on the third stratum *g*]). The associations between psychometric *g* and reaction time *g* (e.g., from the batteries of reaction time tests used by Vernon [1983, 1989]) can reach effects sizes that are large, with *r*'s above 0.5. Vernon (1985; Vernon & Kantor, 1986) tested and refuted hypotheses that factors such as shared content-type, the need for speeded responding, and general complexity level of task were the key factors that produced correlations between psychometric test scores and reaction time variables,

> Rather, it is the *g* factor common to all psychometric variables that accounts for the bulk of the relationship between IQ and reaction time. Further, given the degree of this relationship, it appears that a moderately large part of the variance in *g* is attributable to variance in speed and efficiency of execution of a small number of basic cognitive processes. (p. 69)

However, such extracting of a general factor from a set of reaction time tests would seem to obscure the theoretical interest that the individual parameters were supposed to contain. Often, when reaction time parameters are used as independent variables to predict psychometric test scores in multiple regression equations, there is little additional independent variance added after the first variable has been entered. This result goes against a model that states that each reaction time task is indexing a separate function or set of functions. Partial dissenters from the view that *g* is the locus of most variance accounted for by speed of information processing tests or elementary cognitive tasks are Roberts and Stankov (1999). They found that the chief correlate of speed of processing is the second stratum factor of fluid *g* and that speed of processing itself has a taxonomic structure within the hierarchy of mental abilities (Carroll, 1993). However, they also leaned toward emphasizing the special association between a third stratum *g* and chronometric variables,

> The third-stratum factor extracted from the factor analysis of broad abilities in this study was interpreted as an "inflated" Gf, and subsequently designated GF . . . Table 25 includes the correlations between MTx, DTx, and RTx [movement, decision and reaction times, respectively, of the given chronometric task] with GF for each of the 10 chronometric tasks. Consistent with the assertion that the relationship between processing speed and cognitive abilities occurs at a higher stratum of the taxonomy circumscribing intelligence, these coefficients are among the highest obtained for any psychometric factor extracted in the investigation. (p. 71)

The correlation between psychometric test scores and reaction time parameters from Hick, Posner, and Sternberg tasks, although it is modest, seems largely to be mediated by genetic factors (Rijsdijk, Vernon, & Boomsma, 1998). In one large study of German twins the genetic contribution to the association between the general factor extracted from variables produced by the Sternberg and Posner reaction time tasks was 0.97 for a fluid intelligence factor and 0.81 for a crystallized intelligence factor (Neubauer et al., 2000). This is strong evidence for some causal link between the general variance in psychometric *g* and the cognitive processes measured in the aforementioned tasks. More evidence for the relevance of *g* to currently employed cognitive tasks comes from the finding that adding so called elementary cognitive tasks to batteries of psychometric tests does not alter the predictive validity of *g* (Luo & Petrill, 1999):

> The predictive power of *g* will not be compromised when *g* is defined using experimentally more tractable ECTs. (p. 157)

It is precisely this theoretical tractability that must now be addressed. From the foregoing selection of evidence, reaction time-type tests have relevance to our understanding of *g*, and *g* is relevant to cognitive models of ability that look to reaction time-type measures. The use of theoretically unspecified variables within reaction time measures (in most cases the slope-type variables that attracted initial interest in the reaction time measures do not perform well as predictors of psychometric test variance) and the increasingly common tendency to use conglomerate measures that bundle together several reaction time variables would seem to be moves away from tractability. It is not that the correlation between the *g* factor from psychometric and reaction time tests is uninteresting, it is just that theoretically understanding a factor common to many reaction time variables seems less likely than understanding a single slope measure. If these issues are combined with the fact that reaction time variables often involve response times of several hundred milliseconds it becomes difficult to defend the epithet "Elementary Cognitive Task" that is often used alongside Hick, Sternberg, and Posner procedures (Jensen, 1998a; Luo & Petrill, 1999). Whereas some have suggested that slope measures can be revived with procedures to increase their reliability (Jensen, 1998b), others have tried to explain that slope measures could never contain much variance that would attach itself to psychometric test score differences (Loman, 1994, 1999). Efforts to explore the psychophysiological associations of reaction time-type tasks that relate to psychometric tests scores, including *g*, are laudable but rare (McGarry-Roberts, Stelmack, & Campbell, 1992).

PSYCHOPHYSICAL-LEVEL COGNITIVE CONSTRUCTS AND *g*

If there is to be a valid estimate of some elementary aspect of cognitive functioning we might expect that the psychophysical level would be a good place to look. Spearman (1904) reckoned that sensory discrimination was a fundamental mental activity and Vickers (Vickers and Smith, 1986) thought that the psychophysical measure of inspection time might provide a 'benchmark' test of mental functioning. Measures of sensory discrimination feature in two current fields of research that are relevant to the theme of this chapter: work on inspection times and mental ability test scores, and measures of sensory discrimination in studies of cognitive ageing.

Inspection Times and Cognitive Ability Test Scores

If a subject is asked to make a simple, forced choice discrimination between two equally likely alternative stimuli, in which the feature to be discriminated is well above the threshold for visual acuity, the relationship between the duration of the stimulus and the probability of a correct response is well described by a cumulative normal ogive (Deary, Caryl, &

Gibson, 1993; Vickers, Nettelbeck, & Willson, 1972). The duration of the stimulus, as available to the subject for the processing of information, is assured by its being backward masked after offset. Individual differences in the efficiency with which visual discriminations of this type take place are measured by a procedure called inspection time. In this task the stimulus is two parallel, vertical lines of markedly different lengths. The longer line may appear on the left or right of the stimulus with equal probability. It is well established that there are individual differences in the stimulus duration that subjects require in order to make a discrimination to any given level of correctness (between 50% [chance] and 100% [perfect]). These individual differences correlate with psychometric intelligence test scores with a medium effect size (about 0.4 with some types of ability test; Deary & Stough, 1996; Kranzler & Jensen, 1989; Nettelbeck, 1987). We thus again pass the starting point for a consideration of these findings within the present remit. With such an association between a putatively elementary cognitive ability and psychometric intelligence what emphasis need there be on the construct of *g*?

A semiquantitative review and a meta-analysis of inspection time research suggested that there were stronger correlations between inspection time and nonverbal as opposed to verbal abilities (Kranzler & Jensen, 1989; Nettelbeck, 1987). Whereas the former associations were around or above .4, the latter tended to be around or below .2. This was replicated in a single study involving otherwise healthy people with diabetes who were tested on 9 of the 11 subtests of the WAIS–R (Deary, 1993). In this study a two-factor model of Performance and Verbal ability, in which the two factors correlated strongly and in which inspection time loaded only on the Performance ability, fitted better than a single *g* factor model onto which all nine subtests plus inspection time loaded. A subsequent study examined inspection time and all eleven WAIS–R subtests in a sample of more than 100 people whose age, sex, and social class characteristics were well matched to the Scottish adult population (Crawford, Deary, Allan, & Gustafsson, 1998). This was the first report in which a moderately large general population sample of normal adults had been tested on a recognized battery of tests alongside a valid inspection time measure (based on a light emitting diode device rather than a computer screen). Several competing models of the association between inspection time and factors from the WAIS–R were tested. The best fitting model is shown in Fig. 7.5. This is a nested factors model fitted by structural equation modeling using EQS. The chi square for the model was 61.7 with 43 d.f. The average off-diagonal standardized residual was 0.037 and the comparative fit index was 0.971. By all of these criteria the model fits well. Thus, inspection time has a loading of almost 0.4 on the perceptual–organizational factor of the WAIS–R and a loading of almost 0.2 on *g*. This model performed better

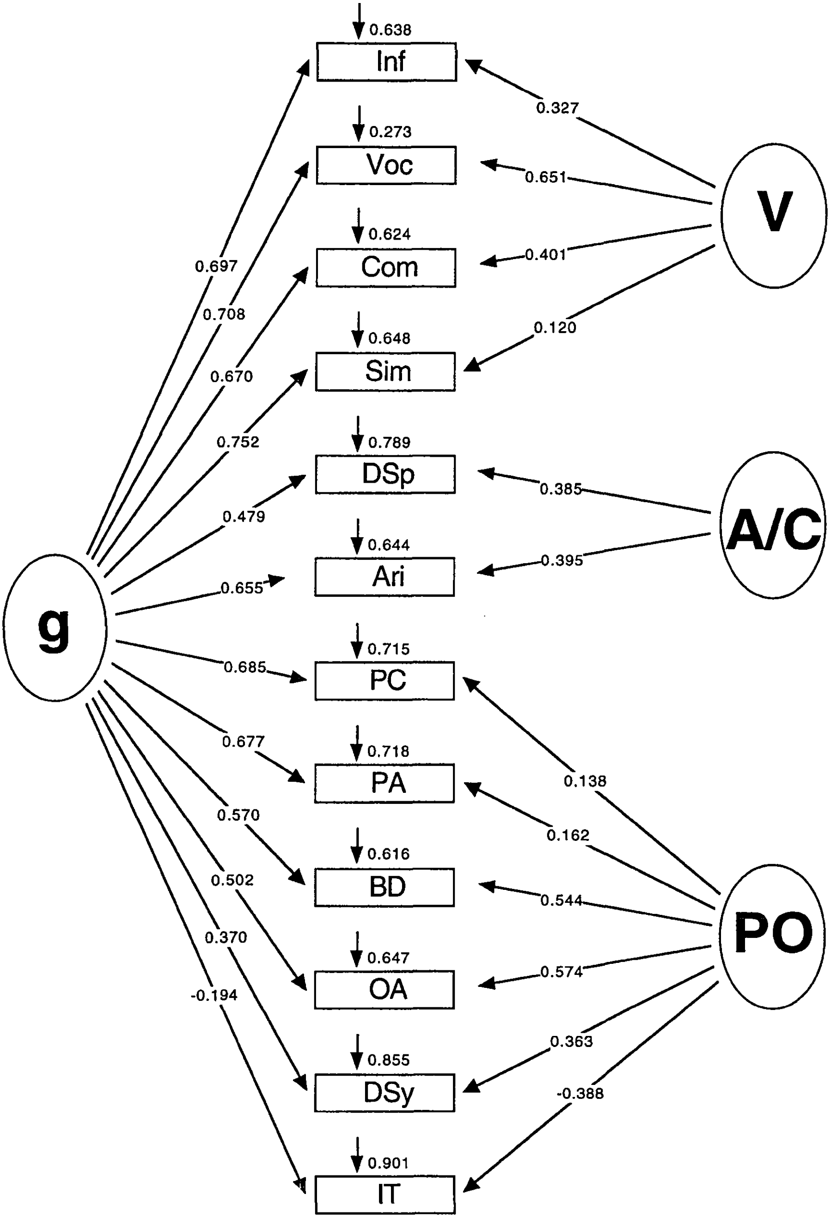

FIG. 7.5. Nested factors structural model of the associations among subtest scores of the Wechlser Adult Intelligence Scale-Revised and inspection times. Note that the general factor (g) of the WAIS-R is orthogonal to the verbal (V), attention/concentration (A/C) and perceptual-organisational factors. Inspection time loads −0.388 on the PO factor and −0.194 on the general factor. This figure was redrawn from Crawford, Deary, Allan, & Gustafsson (1998).

than models that posited the following: (a) a *g* only model; (b) a similar model to that in the figure but in which inspection time loaded on no factors; (c) as (b) but inspection time was constrained to load only on *g*; (d) as (b) but inspection time was constrained to load on only the perceptual/organisational factor; and (e) as (b) but inspection time was allowed to load on all four factors.

Some have interpreted these findings as indicating that inspection time has a special association with fluid intelligence in the Horn–Cattell model. However, data collected by Burns, Nettelbeck, and Cooper (1999) suggested another possibility. They examined inspection time's associations with tests indexing five second-order abilities outlined in Gf–Gc theory. The tests were drawn from the Woodcock–Johnson battery. Inspection time's highest association was with general processing speed (above .4 in a sample of 64 adults) and there was no significant correlation with the marker test for Gf. Note, however, that only one subtest was used to index each supposed factor. The data in the last few paragraphs were obtained on modest sample sizes undertaking only modest-sized batteries of mental tests. They agree to the extent that inspection time's highest correlations might be with some second-order factors rather than a third-order *g* factor. But they impel researchers to conduct more research with larger psychometric batteries, in which several markers tests are used to index each ability factor, so that a better location for inspection time's explanatory possibilities may be charted.

In the model in Fig. 7.5 the factors are orthogonal, which means that inspection time has a significant association with *g* but a stronger association with a factor orthogonal to *g*. The tests among competing models show that *g* cannot be left out of the story with regard to the impact of inspection time, and also that the closer association lies elsewhere. As an endorsement of this, another study (Deary & Crawford, 1998) examined inspection time's performance within Jensen's (1998a) method of correlated vectors. This method examines the correlation between two vectors of correlation coefficients: (a) the strengths of association (loadings) between individual psychometric mental tests and *g*, and (b) the correlation of those mental tests with another indicator of ability (in this case inspection time). The usual result is a high positive correlation (i.e., the indicator typically has the strongest associations with those tests that have the largest *g* loadings). This works for reaction time measures (Jensen, 1998a, pp. 236–238). Inspection time bucks the trend. Three moderately sized studies—involving inspection time or tachistoscopic word recognition, the WAIS–R battery and a near-normal samples of adults—were re-examined (Deary & Crawford, 1998). In all three cases the psychophysical measure failed to show the expected correlated vectors association, with the sign typically being negative: Tests with higher *g* loadings had lower correlations with inspection time. However, others have used Wechsler-type batteries and found that inspection time-type tasks load principally on *g* and/or find a positive correlated vector association (Jensen, 1998a, p. 223; see also Kranzler & Jensen, 1991; Luo & Petrill, 1999).

These results take the inquiry on to some tricky ground. First, it is recollected that psychometric ability test score models do not represent, necessarily, the brain's processing structures. Next, it is asked whether inspection time has validity as a measure of brain processing, and whether, therefore it can inform about the nature of the psychometric factors it associates with. To answer, using the foregoing data, the question of whether a major element of *g* is some form of processing speed begs the questions of, (a) whether the WAIS–R provides an adequate *g* factor and (b) whether inspection time may be said solely or largely to index speed of information processing.

Even if inspection time and other psychophysical processing tasks showed individual differences that were substantially related to psychometric *g*, that association might be more or less interesting. It might be less interesting, especially to those for whom cognitive task–psychometric correlations were a step toward reducing psychometric intelligence differences to something nearer to the brain, if all that was being shown was that some type of general, higher level psychological factor was responsible for the correlations. Candidate higher level factors might be attention, motivation, persistence, test anxiety, other personality traits, cognitive strategy usage, and so forth. These top-down explanations for cognitive/psychophysical–psychometric ability test correlations have competed with so-called bottom-up accounts which assert that the correlations are caused by some shared information processing elements in cognitive/psychophysical tasks and psychometric tests. Discussions of the empirical studies that addressed this issue (Deary, 1996; Jensen, 1998a; Neubauer, 1997) find little evidence that personality, motivation, strategies, or other higher level factors account for the relationships. Progress, though, would be easier if, instead of attempting to refute all such high-level explainings-away of cognitive/psychophysical task-psychometric task correlations, researchers could come up with a validated model of a cognitive task and point to the source of variance that affords the correlation with psychometric test scores. Even for the seemingly simple inspection time the original model of task performance has been seriously questioned and all but abandoned by its originator (Levy, 1992; Vickers, Pietsch, & Hemmingway, 1995). Proper attention is being given to integrating inspection time with other backward masking tasks and theories (Deary, McCrimmon, & Bradshaw, 1997; White, 1996) and the psychophysiological underpinnings of inspection time performance and its association with psychometric ability tests scores have been explored (Caryl, 1994).

Sensory Discrimination, *g* and Cognitive Aging

A fillip to the idea that mental ability differences may largely be captured in a general factor and positive evidence that the general factor to some substantial degree might underpinned by differences in a speed of cognitive processing come from research into cognitive aging. In a number of influential empirical, review, and theoretical papers Salthouse (1996a, 1996b) and colleagues (Kail & Salthouse, 1994) have adduced evidence that supposedly different mental abilities, those often assumed to be subserved by different modules, do not age independently. In fact, cognitive aging tends largely to occur in the factor that is general to a number of different factors of mental ability (see the abovementioned papers and Lindenberger and Baltes, 1997; Fig. 7.6). Next, these authors have shown that age-related changes in cognitive ability test scores may in large part be accounted for by changes in processing speed. That is, the variance shared between mental ability test scores and chronological age is mostly mediated by quite simple tests of speed of processing, such as the WAIS–R digit symbol and similar tests, and various tests of reaction time. Salthouse's review and theoretical articles are particularly impressive for their integration of huge numbers of data sets and their fixedness on the processing speed theory of cognitive aging.

With regard to a cognitive account of *g*, these results from the aging literature are of potentially great importance, even though the cognitively oriented research on cognitive aging tends to take place apart from other information-processing research into psychometric ability test differences in young adults. If cognitive aging occurs largely in *g* (whatever it represents about the brain) rather than specific cognitive modules, and if most of the age-related variance in cognitive aging is mediated via simple measures of speed of information processing, then there is a clear case for stating that *g* is of central importance in this aspect of cognitive life and that a cognitive account (an information-processing account) must address *g* as the main target for explanation. Without detracting from the care and industry that has been involved in amassing the huge data sets that formed these powerful and convincing regularities (Salthouse, 1996b), two factors relating to the mechanisms and implications of these startling regularities should be raised.

First, the account stating that aging of cognitive functions (largely *g*) is mediated mostly via speed of processing is only as convincing as the measures used to index speed of processing. These measures tend to be either digit symbol-type tests (i.e., tests akin to the Digit Symbol subtest of the Wechsler Intelligence battery) or various reaction time tests. The former is a psychometric test and the latter is more clearly taken from the experimental psychology tradition. By absorbing much of the age-related variance in diverse mental abilities these so-called speed of processing tasks

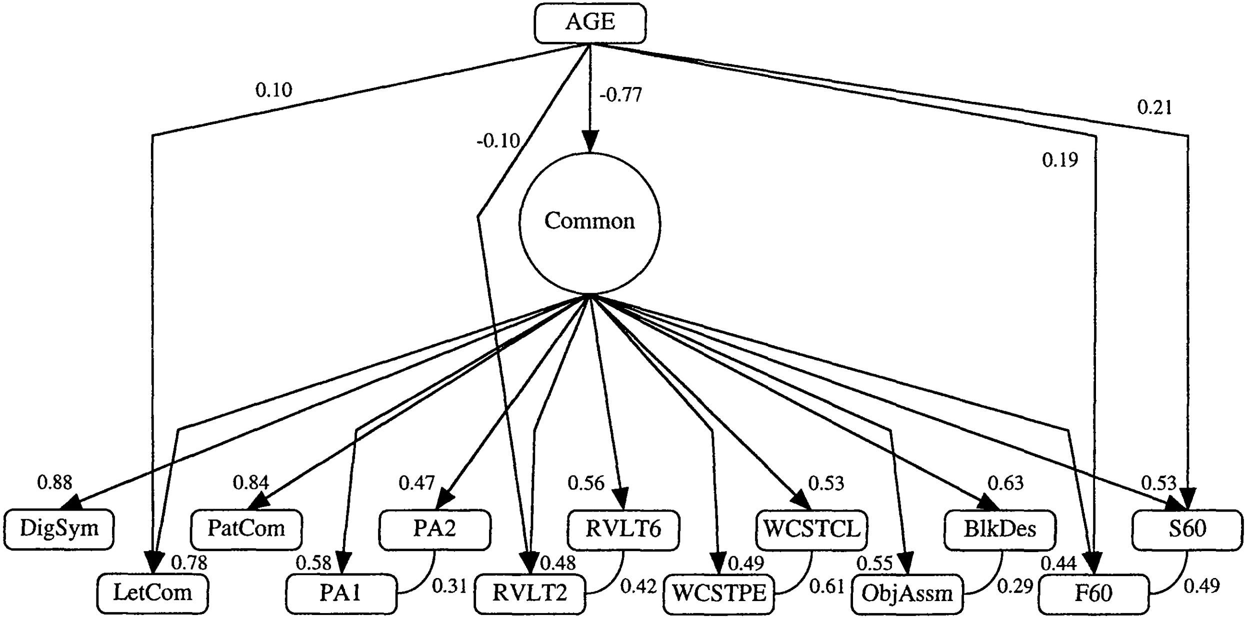

FIG. 7.6. Structural model demonstrating the effects of age on a battery of cognitive abilities. Note that the influence of age is largely on the general (common) factor extracted from the battery of tests. Significant effects of age on specific tests, beyond those effects which are mediated by the general factor, are limited to four relatively small contributions. The tests are: digit symbol from the Wechsler Adult Intelligence Scale-Revised (DigSym), letter comparison (LetCom), pattern comparison (PatCom), Trials 1 & 2 in paired associates memory (PA1 & PA2), Trials 2 and 6 in the Rey Auditory Verbal Learning Test (RVLT2 & RVLT6), percent perseverative errors and conceptual level responses in the Wisconsin Card Sorting Test (WCSTPE & WCSTCL), WAIS-R object assembly and block design score (ObjAssm & BlkDes), and numbers of words produced beginning with F and S in 60 seconds (F60 & S60). This figure was redrawn from Salthouse (1996a).

help us to focus on what might be central to cognitive aging. They cut down much of the complexity surrounding cognitive aging from the cognitive test battery level to the individual task level but they themselves are not understood in mechanistic terms. We are not in a position to offer an elementary account of how humans perform digit symbol or reaction times. The research to date goes as far as our understanding of the brain processes that supports differences in the performance of these tasks.

Second, as long as one inquires after only speed of processing as the mediating variable that accounts for cognitive aging (especially *g*) then one will assume that that is the cause, or that the cause lies in the processes underpinning the tasks that were used to index speed of cognitive processing. But it is possible that processing speed measures appear to mediate age-related changes in cognition because they both correlate highly with something more general about brain changes with age. Relevant to this possibility are the results from the Berlin studies on aging which find that even simpler measures of sensory acuity—vision, hearing, and balance—can largely or entirely mediate the age-related variance in diverse mental abilities (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; see Fig. 7.7). Again, the aging of diverse mental abilities is mediated through *g*. More general still is the finding that the aging of specific abilities, almost entirely mediated through *g*, may be further mediated through biological age acting as a surrogate for chronological age (Anstey & Smith, 1999). This biological age is a latent trait with the following marker variables: physical activity, vision, hearing, grip strength, vibration sense, forced expiratory volume (a respiratory system measure). The authors viewed the marker variables as, "general indicators of the integrity of the central nervous system as well as being sensitive to the aging process" (p. 615).

The foregoing studies on cognitive aging find that the aging of *g* is the bulk of age-related variance, but the field has now come to an interesting point in looking at the mechanisms underlying this aging. Much data suggest that speed of processing might be the key element in age-related change. But growing data sets show that the general decrements in the senses, in psychomotor performance, and even in respiratory function can account for much of cognitive aging. With one stream of research aiming at a specific mechanism underpinning age-related change in the *g* factor, and another insisting that the age changes in *g* are a reflection of general brain (or even wider bodily) integrity, an integration and reconciliation of the two projects is a research priority.

CONCLUSIONS

The question addressed by this chapter is ultimately a rather arbitrary one. Finding associations between psychometric ability factors and validated cognitive elements is an interesting and practically important enter-

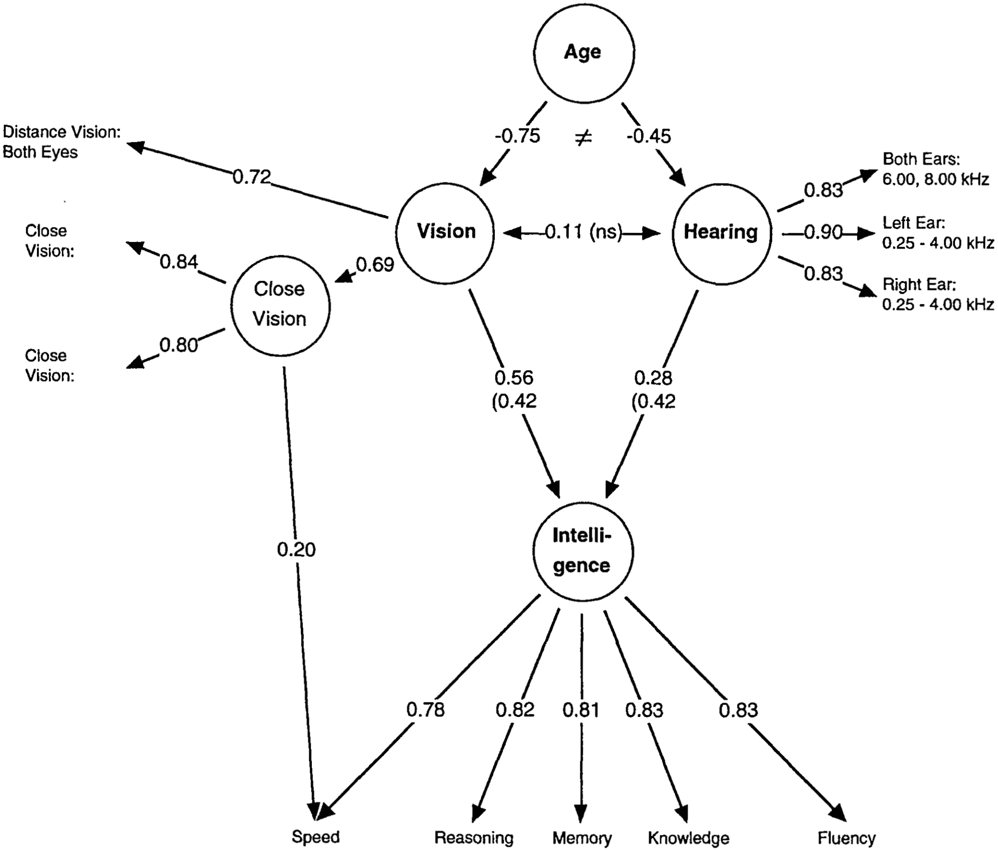

FIG. 7.7. Structural model showing measures of vision and hearing as mediating variables between age and mental ability test scores. Note that the influence of the sensory measures is relatively distinct and is largely on the general factor extracted from the five domains of psychometric ability. This figure was redrawn from Lindenberger and Baltes (1994).

prise. It tries to tie aspects of molar human mental performance to parameters of a cognitive architecture. But the psychometric and the cognitive sides of the equation provide their own brakes to the progression of the field.

Psychometric factors might or might not have isomorphism with the brain's processing mechanisms. Therefore, when cognitive elements correlate with these factors it must be remembered that all that is thereby shown is that the cognitive parameters have a correlation with a test score/factor that has some predictive validity.

Cognitive tasks achieve their importance from two things. First, when they correlate significantly with molar cognitive performance as captured in psychometric tests they obtain a *prima facie* interest. However, to convert this interest into a substantive finding requires that the cognitive task has validity as a parameter within a believable cognitive architecture. How far has cognitive neuroscience progressed in offering such an architecture?

> Exciting new findings have emerged in recent decades concerning the neural underpinnings of cognitive functions such as perception, learning, memory, attention, decision-making, language and motor planning, as well as the influence of emotion and motivation on cognition. With very few exceptions, however, our understanding of these phenomena remains rudimentary. We can identify particular locations within the brain where neuronal activity is modulated in concert with particular external or internal stimuli. In some cases we can even artificially manipulate neural activity in a specific brain structure (using electrical or pharmacological techniques) and cause predictable changes in behavior. But we encounter substantial difficulties in understanding how modulations in neural activity at one point in the nervous system are actually produced by synaptic interactions between neural systems. Thus our current state of knowledge is somewhat akin to looking out of the window of an airplane at night. We can see patches of light from cities and town scattered across the landscape, we know that roads, railways and telephone wires connect those cities, but we gain little sense of the social, political and economic interactions within and between cities that define a functioning society. (Nichols & Newsome, 1999, p. C35)

g stands unassailed as a big concretion of mental test variance. It is a psychometric triumph and a cognitive enigma. When a validated biocognitive model of human mental function finally does arrive, with measurable performance parameters, then we shall begin to understand whether *g* represents some general aspects of brain function or some conglomerate of specific processing functions. Those who want to assert *g*'s pre-eminence possess more empirical support than those who want to wash their hands of it, but that's only because the psychometrics have bedded down far in advance of any cognitive understanding of *g*. In summary, given the current state of knowledge, it is difficult either to disagree with or to state much more than Jensen (1998a), who commented on "The question of the unity or disunity of *g*," as follows,

> The question of whether *g* is the result of individual differences in some single process or in a number of different processes is probably answerable only if one takes into consideration different levels of analysis. At the level of conventional or complex psychometric tests, *g* appears to be unitary. But at some level of analysis of the processes correlated with *g* it will certainly be found that more than a single process is responsible for *g*, whether these processes are at the level of the processes measured by elementary cognitive tasks, or at the level of neurophysiological processes, or even at the molecular level of neural activity. If successful performance on every complex mental test involves, let us say, two distinct, uncorrelated processes, A and B (which are distinguishable and measurable at some less complex level than that of the said tests) in addition to any other processes that are specific to each test or common to certain groups of tests, then in a factor analysis all tests containing A and B will be loaded on a general factor. At this level of analysis, this general factor will forever appear unitary, although it is actually the result of two separate processes, A and B. (pp. 260–261)

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