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Why Is Reaction Time Correlated With Psychometric *g*?

Arthur R. Jensen

It seems almost incredible that individual differences in reaction time (RT) in simple tasks that involve no intellectual content and are so easy as to be performed by most persons in less than 1 s should be correlated with scores on nonspeeded, complex tests of reasoning ability, vocabulary, and general knowledge—the kinds of content that compose IQ tests. Nevertheless, in recent years, the correlation between RT and IQ has become an empirically well established fact, based on thousands of subjects in scores of studies conducted in many laboratories around the world.[1] What might all these studies tell us about the nature of human intelligence? Before trying to answer this question, it is necessary to summarize some concepts and empirical generalizations about the key phenomena.[2]

CONCEPTUAL ISSUES AND EMPIRICAL GENERALIZATIONS

1. We should not use the overextended word *intelligence* in the present context because correlations between RT and scores on psychometric tests reflect only the tests' *g* factor, that is, the general factor common to all measures of complex cognitive performance.[3] The most highly *g*-loaded tests show the highest correlations with RT, and when *g* is statistically removed from the correlation between RT and a psychometric test, the partial correlation coefficient is close to zero. So we are really talking about RT–*g* correlation.

2. The *g* factor per se is a product of individual differences in a wide variety of cognitive abilities. Its conceptual status and empirical reality do not depend on any knowledge of the design features of brain structure and physiology. Even though we know exceedingly little about these design features, we can investigate hypotheses about the basis of individual differences in *g*.

It is most parsimonious to assume that, within a given species, the main structural and functional aspects of the brain are the same for all biologically normal individuals, and that individual differences in cognitive abilities reflect differences in the information stored in long-term memory (LTM) and how that information is represented and organized in LTM. The efficiency of information processing is probably a quantitative, not qualitative or typological, variable, whatever its experiential or biological origins. Because the *g* factor is common to all kinds of cognitive performance, however diverse, it cannot be attributable to any specific knowledge or skill components of performance, but must essentially reflect variance in the speed and efficiency of information processing. The *g* factor is such a distillate from a wide variety of cognitive activities as scarcely to reflect differences in the brain's more specialized design features that may be involved in specific types of ability, which are usually identified at the level of first-order factors, such as verbal, spatial, and numerical factors.

A source of individual differences with such broad generality could conceivably be some simple, even unitary, aspect of brain function, or it could be determined by a number of different properties of the brain that all enter into every kind of complex cognitive activity. At present, we have virtually no knowledge even of the probable number of brain mechanisms involved in *g*, let alone their precise nature. Studies of the RT–*g* relationship may be able to throw some light on this question.

3. Simple RT (i.e., following a preparatory signal, the time to react to the onset of a single stimulus whose nature and location are already known to the subject) has a quite small negative correlation (typically about $-.10$) with *g*. The amount of information processing for simple RT is very small. More of the variance in simple RT is attributable to noncognitive sensorimotor factors than to central information processing. Under conditions of discrimination and choice, which involve the speed of retrieval of information from short-term memory (STM) or LTM, RT (though seldom more than 1 s) is very significantly greater than simple RT—and is also more highly correlated with *g*.

4. In normal young adults, the RT–*g* correlation begins to diminish beyond a level of task complexity that makes for RTs greater than about 1 s. There seem to be two main reasons for this U-shaped relation between the RT–*g* correlation and the degree of task complexity: First, beyond some optimal point, an increase in task complexity invites the development of special strategies for performing the task. The various strategies adopted by subjects are less correlated with *g* than is the

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speed of information processing when everyone is either using no strategy or using the same strategy throughout all trials. Second, when task complexity (and hence difficulty) exceeds a certain point, the subject makes response errors. At or beyond this "threshold of breakdown," individual differences in RT are transformed into individual differences in error rates. Hence, there is a reciprocal relationship between the RT–*g* correlation and the error–*g* correlation, as a function of task complexity.

5. RT decreases in a regular way with age from childhood to maturity, just as one would predict from mental growth curves, rate of brain growth, and increase in the myelination of axons from early childhood to maturity. (Nerve conduction velocity, NCV, is related to the degree of myelination.) RT slows with age in later maturity, mirroring the decline in scores on psychometric tests of fluid *g*, the gradual decrease in brain weight and volume, the demyelination of axons, and the decrease in NCV. Moreover, the information processing aspect of RT is more related to age differences than the sensorimotor aspect. Choice RT and other complex forms of RT show a much greater age gradient than simple RT.

6. All RT tasks have a great deal of specificity; that is, a relatively small proportion of their variance is common to conventional psychometric tests. When a number of psychometric tests and chronometric (RT) tests are factor analyzed together, all the RT measures show up only on the *g* factor and not on the various group factors (verbal, spatial, etc.) of the psychometric battery. But a large proportion of the RT variance also shows up on factors that load only on chronometric tasks; that is, there is a common factor among various chronometric tests that is not shared by psychometric tests. Every chronometric task also has a good deal of uniqueness, in the factor analysis sense, that is, variance which is not common to any other tests or tasks among all those entered into the factor analysis. This relatively large amount of non-*g* variance peculiar to RT tasks is related to sensorimotor, rather than cognitive, factors. Hence, it imposes a severe ceiling on the correlation between any particular RT task and a *g*-loaded psychometric test. This correlation ceiling is generally in the range of .30 to .50 for RT tasks of greater complexity than simple RT. A combination of RT measures based on a number of different tasks, however, has shown correlations with *g* approaching .70, which approaches the average correlation among different IQ tests.

"SPEED" VERSUS "NOISE" THEORIES OF THE RT–*g* CORRELATION

What are the fewest independent sources of variance needed to explain the RT–*g* correlation? Because the RT–*g* relationship will have to be explained ultimately in neurological terms, it seems most productive to suggest hypotheses that involve neurological variables. Some of these neurological hypotheses are testable by presently available means.

Speed

The most obvious hypothesis is that speed of information processing is the essential basis of *g*, and one possible neurological basis of speed of processing is the speed of transmission through nerve pathways, which comprises both NCV and speed of synaptic transmission.

It must be emphasized that information processing speed should not be confused with overt test-taking speed. There is plenty of evidence that speeded tests are generally less *g* loaded than nonspeeded, or "power," tests. And RT is less correlated with scores on speeded than on nonspeeded tests. When a test-speed factor, independent of *g*, is extracted from a psychometric battery of speeded and nonspeeded tests, the test-speed factor has virtually zero correlation with RT.

According to the speed-of-processing theory of the RT–*g* correlation, speed is important because of the brain's limited capacity for processing information. Although there may be multiple independent processing resources, when one's attention is highly focused, as in solving a complex and novel problem that cannot be handled by automatized skills, there is a bottleneck in channel capacity. Also, information coming into the central processing unit (often called working memory, or WM) from external stimuli or from LTM is lost rapidly. If all the information needed for problem solution is not processed before it is lost, it must be taken in again by repetition of the stimulus or repeated retrieval from LTM. Hence, achieving a correct or adequate solution is a race between two variables: speed of processing and rate of decay, or loss, of the information needed. Thus, persons with faster speed of processing have faster RTs on elementary cognitive tasks than persons with slower processing speed, and can also acquire knowledge and skills faster, retrieve information from LTM more efficiently, reason better, and solve more complex problems on mental tests.

The crucial question, then, is this: Does speed of information processing reflect NCV in the brain? If so, we should find a correlation between NCV and scores on *g*-loaded psychometric tests. Vernon and Mori[4] found a correlation (about +.40) between peripheral NCV (in the median nerve of the forearm) and IQ, in two independent samples. However, Reed and I,[5] in a very similar study based on a larger sample, did not find a significant correlation. The reason for the discrepant results has not yet been discovered.

Reed and I[6] did find a significant correlation ($r = +.27$, corrected for restriction of range in IQ = +.37) between IQ and NCV in the visual tract going from the retina to the visual cortex in 147 college males. This pathway is a part of the central nervous system, unlike peripheral nerves, and the characteristics of nerve fibers in the visual tract are much more like those in the higher brain centers involved in complex information processes.

The fact that the correlations are found in nerve tracts that register evoked responses some 200 to 300 ms before the neural impulses have reached the higher brain centers is evidence that the correlation between NCV and *g* is a bottom-up and not a top-down relationship. That is, the higher mental processes reflected in test performance do not influence NCV in the visual tract, but nerve fibers in the visual tract have properties similar to those in the higher centers. Hence, NCV in the visual tract and NCV in the higher association centers are positively correlated. Replication studies of these findings are now under way. If the results hold up, then variance in NCV will have to be considered a basic component of psychometric *g*.

"Noise" in Neural Transmission

The idea of "noise" in information processing was suggested by the finding that intraindividual variability in RT, measured as the individual's standard deviation of RT over *n* trials, is generally more highly correlated (negatively) with g than is the mean or median RT over *n* trials. Intraindividual variability in RT (RTSD) is highly correlated with median RT, but has much lower split-half and test–retest reliability. Eysenck[7] has argued that variance in RTSD, rather than NCV, is the primary or most basic phenomenon, and that the correlated variance in RT is merely a consequence of individual differences in RTSD.[8] Theoretically, Eysenck views RTSD as an index of noise, or errors, in neural transmission of information in the brain. This idea seems highly plausible. I have hypothesized a construct, "neural oscillation," to explain RTSD.[9] I hypothesize that a longer period of oscillation (i.e., slower oscillation) makes for larger RTSD and lower *g*. Noise and oscillation could be causally related phenomena, or they could even be one and the same thing.

The critical question is whether RT and RTSD are simply different indices of the same basic process. Much evidence pertinent to this question has now been analyzed. RT and RTSD are correlated only about .75 after correction for attenuation (i.e., measurement error), indicating that they do not reflect one and the same process. Moreover, when one of the two variables is statistically controlled, it is seen that RT and RTSD are independently correlated with *g*, and the (partial) correlation is larger for RTSD than for RT.[10] Therefore, there seem to be at least two independent components of *g*: variance in NCV and variance in neural oscillation (or whatever mechanism underlies RTSD).

CAPACITY OF WORKING MEMORY

Also, the concept of capacity of WM is needed to account for the RT–*g* relation. WM is the active part of STM. There is now evidence that RT tasks become more *g* loaded as they tend to strain the capacity of WM, yet not strain it beyond the threshold of breakdown and loss of information. Tasks at the level of complexity at which the threshold of breakdown (hence incorrect solution or inadequate response) is reached are the best measures of an individual's level of *g*.

This relationship can be demonstrated with chronometric tasks by means of a *dual-task* paradigm. For example, the subject may be asked to memorize a series of five digits shown for 3 s on a computer monitor. Immediately after the digits vanish, two letters appear. The subject responds as quickly as possible by pressing one of two keys labeled "YES" or "NO" to indicate if the letters are the same. Immediately, a single probe digit appears, and the subject must respond as quickly as possible by pressing the "YES" or "NO" key to indicate whether the probe digit was or was not included in the set of five digits previously presented. RT on each of these dual tasks is longer than when each task is presented separately. Even more interesting, the correlation of *g* with RT on each task is slightly but consistently greater in the dual-task than in the single-task condition. The occupation of WM by the digit series causes a longer RT in the interposed discrimination task, and individual differences in this increment in RT reflect differences in *g*. Thus, we may conclude that an explanation of the RT–*g* correlation also requires a concept of variance in WM capacity.

The notion of capacity is more difficult to handle in neurological terms than is either speed or oscillation. Speed may be equated with NCV and oscillation with the periodicity in the synchronized action potentials of large groups of neurons. Psychologists of the Erlangen school in Germany, however, have formulated the notion of capacity of WM in terms of neurological mechanisms that can be measured independently.[11] They argue that capacity (C), measured as bits of information, is the product of speed (S) of information transmission (or NCV), measured in bits per second, and the duration (D) of the neural traces of information, measured in seconds.[12] Thus, the capacity of WM can be expressed as

$$C \text{ bits} = S \text{ bits/s} \times D \text{ s}.$$

This formula adds yet another basic component, D, to the theory of the causal underpinnings of g. Because two somewhat independent elements, S and D, are involved in capacity, we should expect C to be more highly correlated with g than speed (or RT) alone. Correlations of .67 and .88 have been reported between the experimental measure of C and scores on a highly *g*-loaded vocabulary test in two large samples of adults.[10]

SUMMARY

The proposed hypothesis of the neurological underpinnings of psychometric g and its empirically established correlation with RT comprises three basic sources of variance: (a) speed of information transmission, related to nerve conduction velocity; (b) oscillation, or intraindividual variability in speed of processing, related to synchronous periodicity of activation thresholds of groups of neurons; and (c) duration of neurally encoded information in immediate consciousness, or working memory, reflecting the rate of decay of neural traces that originated from external stimuli or from neurally encoded information brought up momentarily from long-term memory.

This working theory is consistent with present empirical evidence on the correlation between RT and g, and although the neurological aspects are still largely speculative, the hypothesized mechanisms seem worthy of continued empirical investigation. It seems very improbable that the proposed hypothesis will turn out to be wholly correct. The correct theory, however, when finally established by empirical evidence, will probably not be very different.

Notes

1. P.A. Vernon, Ed., *Speed of Information Processing and Intelligence* (Ablex, Norwood, NJ, 1987).

2. For a more detailed explication and citations of specific studies, see A.R. Jensen, Understanding g in terms of information processing, *Educational Psychology Review, 4,* 271–308 (1992).

3. A.R. Jensen, Commentary: Vehicles of g, *Psychological Science, 3,* 275–278 (1992).

4. P.A. Vernon and M. Mori, Intelligence, reaction times, and peripheral nerve conduction velocity, *Intelligence, 16,* 273–288 (1992).

5. T.E. Reed and A.R. Jensen, Arm nerve conduction velocity (NCV), brain NCV, reaction time, and intelligence, *Intelligence, 15,* 33–47 (1991).

6. T.E. Reed and A.R. Jensen, Conduction velocity in a brain nerve pathway of normal adults correlates with intelligence, *Intelligence, 16,* 259–272 (1992).

7. H.J. Eysenck, Intelligence and reaction time: The contribution of Arthur Jensen, in *Arthur Jensen: Consensus and Controversy,* S. Modgil and C. Modgil, Eds. (Falmer, New York, 1987).

8. There is much less variance among persons in their fastest RTs than their slowest RTs. The distribution of any person's RTs is skewed to the right (i.e., toward longer RT). Those persons whose RTs have the most skewed distributions consequently show the largest RTSDs and the longest mean (or median) RTs, and they also have relatively lower IQs, on average. Thus, it is easier to explain RT differences in terms of differences in RTSD than the other way around. In any case, the phenomenon of individual differences in RTSD and its correlation with g is firmly established. See note 10.

9. A.R. Jensen, Reaction time and psychometric g, in *A Model for Intelligence,* H.J. Eysenck, Ed. (Springer-Verlag, Berlin, 1982).

10. A.R. Jensen, The importance of intraindividual variability in reaction time, *Personality and Individual Differences, 13,* 869–882 (1992).

11. S. Lehrl and B. Fischer, The basic parameters of human information processing: Their role in the determination of intelligence, *Personality and Individual Differences, 9,* 883–896 (1988); S. Lehrl and B. Fischer, A basic information psychological parameter (*BIP*) for the reconstruction of concepts of intelligence, *European Journal of Personality, 4,* 259–286 (1990).

12. *D* was measured by forward digit span and letter span, but I would prefer that *D* be measured chronometrically, by the increase in RT in dual as compared with single RT tasks; that is, as the strength of a stimulus trace diminishes over time, the RT for scanning the trace increases, and its rate of increase can index *D.*

Filling in Gaps in Perception: Part II. Scotomas and Phantom Limbs

V.S. Ramachandran

In this article, I present some findings that suggest we need to radically revise two of the basic concepts in neuroscience: the concept of the receptive field as a set of receptors funneling in information onto single sensory neurons and the idea of fixed topography, or "maps," in the adult brain.

My interest in this area began over 15 years ago when, as a student in neurology clinics, I encountered patients with focal lesions in the visual cortex. Such patients usually have what is described as a scotoma[1]—a region in the visual field within which nothing can be consciously perceived. Remarkably, the patients themselves are often unaware of this gaping hole in the visual field. When they look at a colored wall or a regular pattern of any kind (e.g., a carpet or a tile floor), the scotoma gets "filled in" by the surrounding color or pattern. Or if they gaze at a companion seen

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