PERSPECTIVES: COGNITION

The Holey Grail of General Intelligence

Robert J. Sternberg

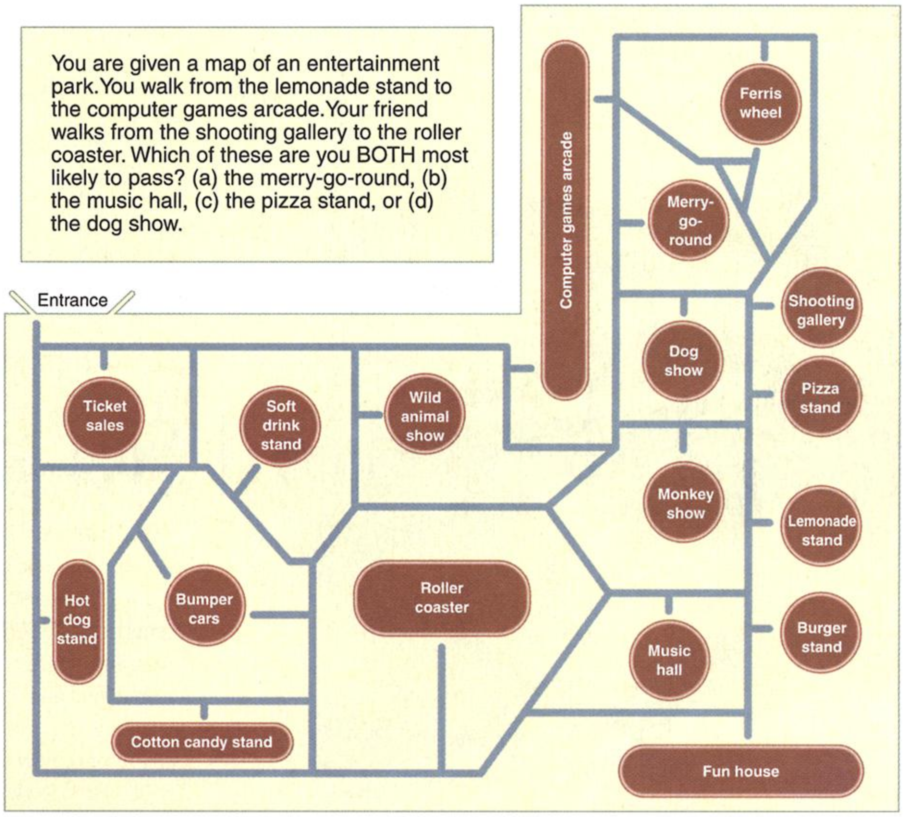
Since the time of Plato, we have been fascinated by the notion of intelligence and how to measure it. In 1904, Spearman proposed the existence of a general factor of intelligence (g), which represents what is general or common to all the abilities that constitute so-called IQ (intelligence quotient). Spearman argued that g contributes to success on a wide range of cognitive tasks. A competing hypothesis put forward by Thomson in 1916 proposed that what appeared to be a unitary general ability was in fact a collection of multitudinous and diverse skills needed to complete most intellectual tasks. Theories such as these have been largely divorced from the development of most tests of intelligence. Such tests have, for the most part, been developed in a theoretical vacuum as measures of analytical skills, and then only related to theories of intelligence post hoc.

To provide a bridge between theories and tests of intelligence, Duncan *et al.* (*1*) have used positron emission tomography to monitor brain activation in volunteers performing different spatial, verbal, and perceptuo-motor tasks. They then asked which hypothesis, Spearman's or Thomson's, was best supported by their PET scan data. On page 457 of this issue they report, consistent with past findings, that performance of tasks that are good measures of g results in activation of portions of the brain's frontal lobes. They interpret this finding as supporting Spearman's hypothesis because one area of the brain (rather than many) is primarily activated when volunteers perform different g-based tasks (although this interpretation is questionable because there is no clearly specified metric for what constitutes one area of the brain versus "diffuse neural recruitment"). But how does any of this relate to intelligence as it operates in the everyday world?

Given that this is the year when a new U.S. president is to be elected, perhaps there is more than usual interest in the testing of intelligence. Three of the more occupationally successful individuals in the United States are Governor George W. Bush, Vice-President Al Gore, and Ex-Senator Bill Bradley, all of whom have been candidates this year for the U.S. Presidency. However they achieved their success, it was not through excellence in the kinds of abilities measured by tests of intelligence. On the verbal Scholastic Aptitude Test, a test of verbal comprehension and reasoning skills with items similar to some of those on intelligence tests, Bush scored 566; Gore, 625; and Bradley, 485 (*2*) (the mean for U.S. college applicants is roughly 500 and the standard deviation 100, with a range of 200 to 800). These notably undistinguished scores were accompanied by equally undistinguished academic records on the part of Bush at Yale and Gore at Harvard, but not of low-scorer Bradley, who graduated magna cum laude from Princeton. It is possible, of course, that notable success in politics depends little on intelligence, but it is also possible that there is more to intelligence than is measured by conventional tests (such as those used by Duncan *et al.*) that assess analytical skills.

Even the two principal originators of contemporary intelligence tests, Binet and Wechsler, recognized the incompleteness of such tests (*3*). Many investigators of human intelligence have been duped by Boring's early operational (and circular) definition of intelligence as what IQ tests measure (*4*). They have become, to some extent, fixated on the simplistic notion of general intelligence. Although IQ tests largely measure g, they include measurement of other, more specific abilities as well.

Support for a yet broader conceptualization of intelligence stems both from modern theories and modern research on intelligence. A triarchic theory of intelligence, for example, has broader notions of the abilities constituting intelligence than either the Spearman or Thomson hypotheses. This triarchic theory postulates a separation of analytical intelligence (the only kind measured by Duncan *et al.*), creative intelligence, and practical intelligence (*5*) (see the figure). This theory has found confirmatory factor-analytical support for the relative independence (statistical separation) of these abilities across different cultural groups, and



Test your intelligence. Conventional tests of intelligence primarily measure analytical skills. More comprehensive tests (based on a broader, "triarchic" theory of intelligence) measure creative and practical abilities as well. These additional abilities are relatively distinct from analytical skills. An example of a test for creativity might be to write a caption for a cartoon. An example of a test for practical skills is given above.

The author is in the Department of Psychology, Yale University, Box 208205, New Haven, CT 06520–8205, USA. E-mail: robert.sternberg@yale.edu

groups of different ages and socioeconomic status (6). Conventional factor-analytical studies may find a *g* factor because they use only a relatively narrow range of tests (7). Moreover, tests of practical intelligence requiring real-world problem solving and decision-making—the kind in which Gore, Bush, and Bradley seem to excel—typically have been found to have only trivial correlations with tests of analytical intelligence, but to predict real-world job performance as well as or better than do analytical tests (8). In one study, the correlations were actually *negative* (9), suggesting that in societal circumstances in which practical skills are highly valued but academic ones are not, intelligent individuals may develop their practical skills at the expense of academic, analytical skills.

The frontal lobes certainly are important for many aspects of intelligence. However, although Duncan *et al.* propose that the neural circuitry of the frontal lobes is the basis of intelligence, they fail to show anything more than a correlational relationship. The fact that a dependent measure correlates with a biological event does not mean that it is caused by this event, because correlation does not imply causation. One cannot tell from a correlation between two variables whether the first variable causes the second variable, the second variable causes the first variable, or both variables are dependent on some third higher order variable. It is well established that learning alters the structure and function of the brain (10). Moreover, studies of individual differences in brain activation patterns as measured by PET scanning suggest that more intelligent people often show less, not more of certain kinds of frontal activation when they are performing analytical tasks (11), presumably because they find the tasks less challenging than do less intelligent people. Thus, the fact that areas of the brain are activated during some kinds of intelligent thought does not mean that their activation is the cause of these thought processes. Moreover, the Duncan study does not indicate whether these same areas are activated during creative or practical thought, or during the thought required for people to be intelligent in their everyday lives.

The mental-atlas approach taken by Duncan *et al.* (dating back to the time of the phrenologist Gall) implies that the understanding of intelligence depends upon finding the locus or loci of intelligence in the human brain. Their claim is similar to the weak claim that we understand the intelligence of a computer when we localize its artificial intelligence in a silicon chip embedded deep within the hardware. To understand human intelligence we must first unravel the functional significance of the frontal lobes and the elements contained therein and learn how operations in the designated areas are connected with the tasks that people perform.

Plato was among the first to recognize the brain as the seat of intelligence. It is sobering to realize that our progress since Plato is the alleged localization of intelligence to a certain part of the brain rather than an understanding of how the brain or anything else can produce the kind of achievements that the world has seen from Gore, Bush, or Bradley, or from Einstein, Darwin, or Galileo, for that matter. The results of Duncan *et al.* provide a holey grail rather than the Holy Grail, because as yet they have not provided the whole grail.

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PERSPECTIVES: RNA STRUCTURE

Ribozyme Evolution at the Crossroads

Gerald F. Joyce

It is a fundamental tenet of biology that the amino acid sequence of a protein determines its structure, which in turn determines its function. If two proteins have a similar sequence, then their structures and functions are likely to be similar. The same may be said of RNA molecules that behave as enzymes (called ribozymes). Sequence similarity between two such RNA molecules implies that they have the same structure and function. Or does it? On page 448 of this issue, Schultes and Bartel (1) present an example of one RNA sequence that can adopt two completely different structures, each having a distinct catalytic activity. Furthermore, they demonstrate that a continuum of mutations in this common RNA sequence leads in a stepwise manner to sequences that are optimized exclusively for one catalytic activity or the other. This shows that smooth evolutionary pathways exist between distinct ribozymes, facilitating the rapid evolution of RNA-based catalytic activities.

The two catalytic activities selected by the investigators have no evolutionary relationship. One activity is the cleavage of RNA catalyzed by the hepatitis delta virus (HDV) ribozyme, which assists in the replication of HDV viral RNA (2). The other is RNA ligation catalyzed by the class III ligase ribozyme, an activity obtained in the laboratory through "test-tube" evolution (3). The two catalyzed reactions have distinct mechanisms (see the figure). RNA is cleaved by the HDV ribozyme through attack by an internal 2′ hydroxyl on the adjacent phosphate, forming a 2′,3′-cyclic phosphate and releasing an oligonucleotide 5′-hydroxyl. RNA ligation by the class III ligase occurs through attack by the terminal 2′-hydroxyl group of an oligonucleotide substrate on the α-phosphate of an oligonucleotide 5′-triphosphate, forming a 2′,5′-phosphodiester linkage and releasing inorganic pyrophosphate. The two ribozymes have approximately 25% sequence similarity (no more than would be expected by chance) and adopt completely different secondary and tertiary structures.

After careful examination of the HDV and class III ligase ribozymes, Schultes and Bartel constructed an "intersection sequence" that simultaneously satisfied the requirements for both catalytic activities. This is no small feat. Imagine generating a string of text that, without changing the order of a single letter, could be grouped into different words so as to provide two paragraphs that have entirely different meanings. This would be a near-impossible task with an alphabet of 26 letters (or 20 amino acids), especially if the paragraphs (or proteins) had a complex structure. The task is less difficult with RNA molecules because they contain only four "letters"—A, U, G, and C. Furthermore, the letters are interchangeable in a pairwise fashion (maintaining Watson and Crick pairing) within stem structures or in-

The author is in the Departments of Chemistry and Molecular Biology and the Skaggs Institute for Chemical Biology, The Scripps Research Institute, La Jolla, CA 92037, USA. E-mail: gjoyce@scripps.edu