Chapter 9

General Intelligence: Cognitive and Biological Explanations

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In this chapter, I consider the status of the concept of general intelligence and its explanations with special emphasis on biological explanations. First, I discuss *g* as a scientific construct and itemize the objections that have been raised against *g*. Second, I consider cognitive explanations of general intelligence and whether or not such explanations are capable of explaining *g*. Third, I survey attempts to relate *g* to brain functioning and consider the acceptability of various explanations that have been proposed. The emphasis in this chapter is on the potential of explaining *g*.

Many researchers make an assumption about *g*. They assume that it follows a logical, hierarchical chain of explanation: *g* can be explained by cognitive processes that, in turn, can be partly explained by biological variables. On the surface, such an explanatory chain seems reasonable. But is it? This issue deserves more consideration than it has received.

THE CURRENT STATUS OF *g*

When most people discuss intelligence, what they really mean is *g*, or general intelligence. Among researchers, *g* has become synonymous with intelligence. No concept in the social sciences is better established or more substantially validated than *g*. Jensen's (1998) recent book, *The g Factor*, provides overwhelmingly extensive support for the concept and its importance. Despite the support for this construct, a number of objections are frequently raised against it. Before considering how *g* can be explained, it would probably be wise to consider if it is worth explaining. Do any of the objections raised about *g* negate its use as a valid scientific construct?

g AS A SCIENTIFIC CONSTRUCT

One way of asking if *g* is a valid scientific construct is to compare it to other scientific constructs that are generally agreed to have validity. The construct that suggests itself as obvious for comparison is the other *g*, gravity. I think few would argue with gravity as a valid scientific construct. If the *g* of general intelligence has the same scientific characteristics as the *g* of gravity, by analogy, we can conclude that both have equal scientific status. In the following sections, I compare general intelligence to gravity with respect to many of the objections raised against general intelligence. To avoid confusion and subscripts, I use *g* to refer to general intelligence and spell out gravity.

Nobody Knows What *g* Is

One of the common arguments against *g* is that nobody really knows what it is or how to explain it. This comment is true at a theoretical level. Empirically, *g* is well defined but, theoretically, we have only vague ideas about how to explain it. At the empirical level, *g* is the first general factor of a battery of mental tests. Theoretically, there are numerous speculations about what *g* could be but none are presently considered completely adequate.

How does this compare to gravity as a scientific construct. It may come as a surprise to many that gravity has a scientific status almost identical to *g*. Empirically, gravity is well defined but theoretically, there is no scientific agreement about how to explain it. Gravity has been mathematically defined at least since Newton and its effects were well understood even before that. It is well known that bodies attract each other in direct proportion to their mass and in indirect proportion to the distance between them. However, why this occurs is one of the great puzzles of modern physics. After Einstein presented his general theory of relativity, he spent the rest of his life attempting to develop a unified field theory. The goal of this theory was to unify physical forces into a single explanatory theory. Neither Einstein nor anyone else has accomplished this goal. So gravity is as much of a mystery as *g*. Being unable to explain a scientific construct is hardly grounds for objecting to it.

There are numerous other examples of scientific constructs that were widely accepted before they were understood. Genes were so completely accepted as a scientific construct that their effects were described in detail before anyone had seen a gene or even knew their composition. When atomic microscopy was finally used to photograph a single gene, the event went largely unheralded.

In summary, a scientific construct is still valid even if it cannot be completely explained. Indeed, if a complete explanation were required to accept a construct as valid, there would be few or no valid constructs.

g Is Based on Factor Analysis

Another argument against *g* is that factor analysis is used to demonstrate it. This argument generally takes the following form: Factor analysis has a number of technical ambiguities and there is no exactly agreed upon method of measurement. Often investigators will find somewhat different results with the same data set because they use different methods. Because no one is able to measure *g* precisely and exactly, it is not useful as a scientific construct.

This argument amounts to suggesting that bad math invalidates the construct of general intelligence. What the argument fails to do is separate the construct from the measurement method. Even if everything critics say about factor analysis is true, there is no denying that mental tests are positively correlated among themselves. This is the fundamental insight provided by the concept of *g*.

The scientific concept of gravity had its mathematical problems in its development. From Keppler to Galileo to Newton to Einstein, many of the debates about gravity were really arguments about mathematical representation. How should orbits of planets be characterized? How should falling bodies be described mathematically? Indeed, the history of physics is intimately intertwined with the history of mathematics. Despite imprecision in the mathematical representation of gravity, it is hard to argue that imprecision invalidated the construct. The fundamental insight advanced in the concept of gravity is that bodies exert an attractive force on each other. Scientific advancement is certainly related to the precise description of any scientific construct. But inadequacies in the construct's measurement hardly invalidate the construct.

There have been similar advances in the measurement of *g*. Spearman's (1904) first efforts to describe *g* were very crude. Factor analysis has developed into a much more mathematically sophisticated method than those first early efforts. Some would even argue that most of the mathematical arguments about how to define *g* have been settled (Carroll, 1993, Jensen & Weng, 1994). However, the concept of *g* has not changed significantly since those first efforts. *g* simply summarizes the positive relationship between mental tests just as gravity summarizes attractive forces between objects. Again, we find substantial similarity between *g* and gravity.

Mathematics is the language of science. Many mathematicians would say that the history of science is the history of mathematics. This seems to be an oversimplification. Concepts exist independently of the mathematics that define them. Mathematics helps us to define the concept and communicate it. However, the idea of gravity being an attractive force between masses was well established from the time the effort to describe it began. Certainly there were those who resisted the concept. The clergy resisted the idea even after it had become a scientifically and mathematically established fact. It wasn't gravity that they objected to but the change from a geocentric to a heliocentric solar system. Man was no longer at the center of the universe. This change in perspective challenged basic assumptions of organized religion.

Similarly, the idea of *g* has been resisted. Although no one I know of has spent time under house arrest as Galileo did, there has certainly been strong, emotionally laden resistance (Gould, 1981). I think the real reason for this resistance is that *g* appears to limit individual choice. *g* implies that if you are good at one thing, you will be good at everything. It implies that some people will be better than others. This suggestion is anathema to those who believe in a literal interpretation of a fundamental principle that "all men are created equal." They regard a literal equality of ability as fundamental to political equality and, ultimately, democracy or socialism, depending on the writer. In my opinion, this objection is a misinterpretation of what the goals of equality, democracy, and socialism should be. Individual differences exist and the current challenge to social philosophies is how those differences will be accommodated. Social philosophies must adjust to empirical realities.

g Is a Statistical Artifact

Another argument against *g* is that it is a statistical artifact. According to this argument, *g* can be demonstrated statistically but has no existential reality. That is, although one can make a good case for *g* with statistical evidence, there is no such thing as *g*. No one will ever find a place in the brain where *g* is located or even specific cognitive processes that reflect *g*.

The identical thing can be said of gravity. It is unlikely that anyone will ever show you a jar of gravity. Although there have been some suggestions that gravity is a substance, most current theories make no such claims. Obviously, it is important whether a thing exists or not. However, with respect to the scientific status of a construct, existential reality is only important to the purest of scientific realists and there are very few of those.

There are many useful scientific constructs that do not exist as a thing. Examples are hunger, extroversion, and heat to name a few. Even if *g* can only be demonstrated statistically, it is still a legitimate scientific construct. Scientific legitimacy is determined by the extent to which a construct provides explanations for observed phenomena. A massive amount of data show that *g* is a powerfully explanatory construct.

g Depends on the Test Battery

One objection often raised against *g* is that it is dependent on how it is measured. To determine how *g*-loaded a particular test is (call it Test X), one must factor analyze Test X within a battery of other mental tests. The factor loading of the first principal component for Test X indicates its *g*-loading. This *g*-loading will be somewhat dependent on what other tests are included in the battery. Change the other tests in the battery but still include Test X and the *g*-loading of Test X will change slightly.

One reply to this argument is that the change in *g*-loading is only experimental imprecision. If the battery of tests is made very large, the addition or deletion of a few tests will have little or no effect on other tests. If the battery could be made infinitely large, every test would have a fixed *g*-loading.

Comparisons of *g* with gravity show remarkable similarities. Gravity has been notoriously difficult to measure exactly. Gravity varies from place to place. The value of gravity is different on the moon than on the surface of the earth. In fact, gravity differs over the surface of the earth. There is a long history in experimental physics of attempts to obtain accurate measures of gravity. Initially, measurements were taken using pendulums. The history of these experiments is an interesting one progressing toward increasingly accurate measurement. Gravity is still very difficult to measure though more sophisticated instruments have been developed. None of the problems with measuring gravity had any substantial impact on the status of gravity as a scientific construct. Even though nobody knows exactly what gravity is and even though it is not possible to accurately measure gravity, the force of gravity on the moon was predicted and well known before any human set foot there.

There Is No Such Thing as *g*

This issue was touched on earlier. When this criticism is made, it could mean two possible things. The first and most severe criticism is that the operations used to specify *g* fail to show it. This would essentially be an argument that factor analysis shows no *g* and by extension that mental tests are not correlated with each other. To my knowledge, this is one criticism that has never been seriously made. As mentioned earlier, the evidence for *g* is overwhelming and very easy to find.

The second form of this argument is the more common one that was discussed briefly before. In this form of the argument, it is said that *g* has no existential reality. As indicated earlier, *g* need not exist to be a valid scientific construct just as gravity need not exist to be useful as a construct. A variant on this argument accuses those who study intelligence of reifying *g*. Reification is the process of treating a construct that may not exist as if it does exist. The major problem with reification is that it can cause scientists to look for things that don't really exist. For example, the reification of gravity would cause scientists to look for some substance called gravity. If no such substance existed, much time could be needlessly wasted. There are many examples in science of searches for things that had no existential reality. Although such searches may complicate the course of science, they do not invalidate a construct.

Variance Beyond *g*

Some researchers have argued that additional or new constructs are necessary to explain intelligent human behavior. In recent years, such conceptions have rapidly multiplied. They include constructs like practical intelligences, emotional intelligence, social intelligence, and multiple intelligences. There are two ways to look at these constructs. First, they can be viewed as replacing standard conceptions of *g*. To support this stand, any alternative conception of intelligence would be subject to the standard scientific tests that any scientific concept must pass. The proposed construct would have to be more explanatory than any other established construct, including *g*. No construct that I am aware of has come close to meeting this test. In fact, the inventors of these constructs, to my knowledge, have never intended that these constructs replace *g*.

The second approach is to regard new constructs as supplemental to *g*. In this approach, the construct is viewed as an addition to the prediction made by *g*. There is no doubt that such constructs are needed. At its best, *g* can predict only about 50% of the variance in any particular outcome. More usually, *g* predicts about 25% of the variance. This leaves between 50% and 75% of the variance to be explained and something must explain it. The test of whether such constructs are scientifically useful is if they can add predictive validity to what *g* already predicts. This is sometimes called incremental validity. Some of the concepts that have been proposed as supplements to *g* do add incremental validity. Unfortunately, so far this incremental validity seems to be small, usually under 10%. However, even small amounts of incremental validity can be useful in the appropriate prediction situation.

Is there any parallel to this situation with respect to gravity? Yes. As mentioned earlier, Einstein attempted to develop a theory of forces that would include not only gravity but all forces of nature. He was never able to do it but others are still trying. Besides attempts to find concepts that would replace or subsume gravity, there have been other forces identified in the physical world that add "incremental validity" to gravity. These forces are familiar to anyone who has taken a basic physics course (e.g., magnetism).

In the previous sections, I examined the status of *g* as a scientific construct by comparing it to gravity. As a scientific construct, *g* seems nearly identical to gravity in its scientific status. Although arguing by analogy can be dangerous, there seems to be no valid reason to believe that *g* should be rejected as a scientific construct. The next thing to be considered is if basic cognitive processes can be used to explain general intelligence. Like gravity, general intelligence presents an empirical riddle, a scientific juggernaut. We know that mental tests are correlated with each other, but why are they?

COGNITIVE EXPLANATIONS OF *g*

Since the 1980s, perhaps more attention has been given to studying the relationship between cognitive processes and general intelligence than any other area of research on intelligence. Those who have examined cognitive processes as an explanation for *g* have taken several different approaches based on different assumptions. These assumptions and the appropriateness of the approaches they generate are seldom examined.

Can *g* Be Explained in Terms of Cognitive Processes?

The first question to be addressed is if general intelligence can ever be explained by cognitive processes. Although it is a prevalent assumption that cognitive processes can explain *g*, there are those who argue that it may not be possible. In fact, there is no strong evidence for a necessary connection between cognitive processes and *g*. For the most part, correlations between basic cognitive processes and *g* are low, often under .30. It is possible that cognitive skills like memory, attention, and basic learning processes have nothing to do with intelligence. It could be that intelligence tests test something different than basic cognitive processes. Intelligence tests do appear to depend heavily on learned information like vocabulary and other kinds of acquired information. The assumption has generally been that even if intelligence tests do rely on learned information, that learned information depends ultimately on a person's basic cognitive skills because they must use those skills to acquire information. However, some have argued that the acquisition of information does not depend on basic skills so much as opportunity and the development of appropriate strategies for information acquisition (e.g., Ceci & Liker, 1986).

There are several arguments strongly suggesting that cognitive skills must underlie and be responsible for the information we learn. First, and most important, it is possible, using twin samples, to determine if general intelligence and cognitive abilities are based on common genes. When this is done, it is found that tests of basic cognitive ability have a common genetic basis with more complex tests of intelligence (e.g., Petrill, Luo, Thompson, & Detterman, 1996). Further, general intelligence and academic achievement share a common genetic base (Thompson, Detterman, & Plomin, 1991). These findings argue for a common biological basis for a path from basic cognitive tasks to general intelligence to academic achievement.

Second, there are literally thousands of studies from infancy to adulthood that show basic cognitive skills like attention, memory, and perceptual skills determine rate of learning for individuals in experimental situations. To assume that such skills have no impact on the learning of information like that found on intelligence tests defies credibility. Such an assumption would suggest that basic attentional, memorial, and learning skills are entirely learned and that ability is a transitory concept. However, we know that large individual differences can be demonstrated shortly after birth and are reasonably stable throughout the lifespan (e.g., Fagan & Detterman, 1992; Fagen & Haiken-Vasen, 1997).

For these reasons, it seems very likely that cognitive abilities will be involved in the prediction of general intelligence. How, exactly, might *g* and cognitive abilities be related? Several possibilities have been suggested or implied. First, *g* might be predicted by a single cognitive ability. A second possibility is that *g* might be predicted by a set of cognitive abilities. A third possibility is that *g* might be predicted by the relationship among cognitive abilities, that is, by the characteristics that derive from the configuration of cognitive abilities within a complex system. I consider each of these possibilities in order.

Explanations in Terms of a Single Cognitive Process

What would be necessary to show that a single cognitive process was the cause of *g*? As a preliminary, it would be necessary to show that the candidate cognitive process had a high correlation with general intelligence, preferably above .80 before correction for unreliability. Such a correlation would indicate that the process in question accounted for most of the reliable variance of *g*. In fact, there are statistical tests to determine if two variables are actually perfectly correlated with each other once reliability of each test has been taken into account. Application of such a test would be a much stronger criterion than just a high correlation. To the best of my knowledge, no one has ever applied such a high criterion.

A second criterion for accepting any cognitive task as explaining *g* is that the task is a basic cognitive task. What the task measures must be clear and it must be simpler than the complex tests that usually constitute measures of *g*. It would not be explanatory to include tasks as complex as those found on most intelligence tests and then consider this a basic cognitive task. It would simply be a case of one intelligence test correlating highly with another and that is not surprising news.

Several candidates have been suggested as possibilities for a single cognitive process that could explain *g*. Most common of these is speed of processing as indexed by measures of reaction time and other speeded tests. Most measures of speed of processing have not correlated with *g* more highly than about .60 even when unreliability has been taken into account (Kail, 2000; see Vernon, 1987 for reviews). These correlations are not high enough to regard speed of information processing as a possibility for accounting for *g* on its own. In most studies, correlations between *g* and measures of speed of information processing are more often around .30, which is about average for most cognitive tasks.

Another concept closely related to speed of information processing is efficiency of processing (Bates & Stough, 1998). Efficiency not only includes speed but also usually some measure of accuracy. Efficiency of information processing has fared no better than speed of information processing in explaining *g*. Even when modifications in the reaction time procedure are made to improve measurement characteristics, the maximum absolute correlation between the measure of efficiency and *g* is not over .60.

Still another class of cognitive tasks that have been suggested as explaining *g* are those that measure cognitive capacity. In particular, working memory has been identified as one possibility (Embretson, 1995; Kyllonen, 1996). Measures of working memory often do provide the requisite high correlations for explaining *g*. However, when the tasks used to operationalize working memory are examined, they are found to be quite complex. The tasks that have been used to define working memory are often as complex as IQ tests, themselves. For example, Embretson (1995) used indices of progressive matrices-like items to define working memory load.

When the tasks are not as complex, the correlations are substantially lower. Although working memory capacity offers an interesting possibility of a variable that can explain *g*, to be convincing the fundamental processes that compose these tasks will have to be identified. Until that is done, saying working memory explains *g* is nearly the equivalent of saying that *g* explains *g*.

Another idea that has been advanced to explain *g* is complexity. It has been noted that as cognitive tasks become more complex, the correlation between the cognitive tasks and *g* rises. Obviously, task complexity itself is not a cognitive variable. It is simply a description of stimulus characteristics. There must be some single underlying cognitive process that might explain why complexity increases a task's correlation with *g*. One possibility, suggested by Spearman, was the deduction of relationships. As tasks become more complex, it may be more difficult to deduce the relationships involved in the task. However, when the tasks become complex enough to correlate highly with *g*, they are as complex as items that compose *g*. Like working memory, unless a model that specifies the exact cognitive processes involved in complexity is developed, complexity is not a good explanatory construct.

In summary, none of the single variable constructs that have been proposed to explain *g* do so convincingly. Of those that have been considered, working memory and complexity offer the most potential for further exploration. They provide the requisite high correlations but when they do, the tasks used to define these concepts are often as complex as items on intelligence tests that define *g*. Therefore, they are not very explanatory of *g*. To be useful, these constructs will have to be supplemented by a model of exactly what it is that causes them to correlate with *g*.

Explanations in Terms of Multiple Cognitive Processes

Another possible way of explaining *g* is in terms of multiple cognitive processes. That is, multiple basic cognitive processes might contribute separately to explain *g*. If this is so, then it should be possible to combine the contributing cognitive processes in a multiple regression equation and predict *g* at high levels, above .80. It should also be possible to devise a model in which each contributing cognitive process is uncorrelated with others, that is independent. Such a model would describe the sources of individual differences that produce *g*. It would specify the various processes that contribute to attention, learning, and memory.

Detterman et al. (1992) and Detterman (1992) developed a set of cognitive tasks that were computer administered. The development of these tasks was based on a model of information processing developed after a review of the literature. The tasks included measures of reaction time, learning, memory, and other basic cognitive tasks known to be related to intelligence. Each task provided several measures of performance including both speed and accuracy measures. The battery of 10 tasks was given to persons with mental retardation and college students along with a standard intelligence test. The measures from the battery of basic cognitive tasks were then combined in a multiple regression equation to predict general intelligence. It was found that the measures combined to predict general intelligence. The basic cognitive measures predicted intelligence as well as intelligence tests predict each other. In nearly all cases, the multiple correlations were above .80. This finding has been confirmed in larger samples (Detterman, 2000).

Unfortunately, when an attempt was made to fit the data to the original model used to select the variables, the fit was not good. The data also failed to fit several modifications of the original model. The reason the data failed to fit any of the models considered may have to do with measurement of the processes in question. Although the different measures from the 10 tasks had low correlations with each other, they were still correlated. That means they were not pure measures of a single psychological process. If they had been, they would have been uncorrelated with each other.

Logical consideration of any single measure suggests that it will be very difficult, if not impossible, to get a "pure" measure of a cognitive process. The reason is that in any behavioral measure there must always be some kind of sensory stimulus input (encoding) and some kind of motor output (response). Both encoding and response factors must be included with whatever process is being measured. Even if two processes being measured are completely independent of each other, they can still be correlated because of common encoding and response factors. Until adequate methods are found to factor out encoding and response factors, the best measures of independent cognitive processes will remain correlated because of this contamination.

Another problem in identifying basic cognitive processes is that much of what we know about cognition was learned in an effort to develop general laws of cognition. This is what has been called nomothetic research. Most individual differences researchers draw from the knowledge base developed by nomothetic researchers, at least in the early stages of their work. Most of the concepts of attention, learning, memory, and perception used in individual differences research have been directly obtained from nomothetic research.

Although it would seem logical to adopt models from nomothetic research to study individual differences, there can be serious problems. Nomothetic researchers consider individual differences only as "error variance" and regard differences between subjects' performance as nuisance. Because they have no interest in individual differences, they pay little attention to task reliability. Even worse, from a nomothetic perspective the best tasks are those that show little or no individual differences. So tasks developed by nomothetic researchers may be unreliable.

Because of these problems, models developed to describe nomothetic research outcomes may be completely useless when it comes to explaining individual differences. That means that if multiple cognitive processes are required to explain *g*, the most familiar models of cognition may not be very useful. New models may have to be devised with special reference to individual differences.

Kranzler and Jensen (1991) attempted to determine if *g* is actually composed of independent basic cognitive processes. They administered a set of basic cognitive tasks and a measure of psychometric *g* to a group of subjects. They reasoned that if *g* was a single thing, the battery of cognitive tasks would yield a single factor, a general factor. Further, this single factor from the basic cognitive tasks should correlate highly with psychometric *g* obtained from more complex intelligence tasks. On the other hand, if there were multiple independent cognitive processes underlying psychometric *g*, then the battery of basic cognitive tasks should yield multiple factors and each of these factors should be correlated significantly with psychometric *g*. This second result is one they obtained. Even though the battery of basic cognitive tasks was somewhat restricted in the processes measured, they obtained four factors each of which correlated significantly with psychometric *g*. They concluded that psychometric *g* is composed of a number of independent cognitive processes.

Carroll (1991) argued that the Kranzler and Jensen demonstration was not sufficient to show that psychometric *g* was composed of independent processes. Basically, Carroll asserted that the factors Kranzler and Jensen had obtained from the battery of basic cognitive tasks were cross-contaminated causing them all to correlate with psychometric *g*. Because of this contamination, Carroll considered it more parsimonious to regard psychometric *g* as represented by a unitary underlying process. Despite several exchanges between Kranzler and Jensen and Carroll, Carroll remained unconvinced by the Kranzler and Jensen argument even though the Kranzler and Jensen argument became increasingly more refined as the debate progressed.

Despite Carroll's arguments, Kranzler and Jensen support the possibility that a set of independent cognitive processes may be required to account for psychometric *g*. At the very least, the methodology they employed should be a useful one for resolving the issue in the future. It would be interesting to see what would happen if a larger, more diverse set of cognitive tasks than used by Kranzler and Jensen were employed.

In summary, there are some good reasons to believe there are at least several underlying cognitive processes that contribute to *g*. There are several reasons for this conclusion. First, it is possible to use a battery of basic cognitive tasks to predict *g*. Even though the measures obtained from the basic cognitive tasks have moderate to low correlations with *g*, these tasks combine to predict *g*. Second, when a battery of basic cognitive tasks are factor analyzed, factors beyond the first are significantly correlated with psychometric *g*.

There are also some problems in concluding that *g* consists of a set of independent processes. First, it has been very difficult to identify exactly what the independent processes underlying *g* actually are. Second, none of the models of cognitive processing have had much success in fitting the data. Third, the findings that support independent basic cognitive processes, some have argued, can also be explained by a unitary construct and measurement errors.

Explanations in Terms Derivative of Cognitive Systems

Even if *g* is composed of a set of independent cognitive processes, *g* may not be derived from those processes. It could be that *g* results not because of any particular set of basic cognitive processes but because of the relationship among those processes. Detterman (1987, 1994a) proposed a system theory of general intelligence that suggests that *g* really results from the relationship among components of the cognitive system. According to this theory, cognitive components are independent but are integrated together into an interactive system with a high degree of wholeness. In system terminology, wholeness means that the parts of the system are highly interdependent on each other. Some of the components are more central to the operation of the system. If a process is a central one, it is used by a high proportion of the system's other parts. Thus, many system paths lead through a central process. Therefore, if a central process is congenitally weak or has been damaged, it will have a widespread effect on the system because so many other parts of the system rely on the central process. Detterman proposed that *g* resulted from a defect in one or more central processes. The damaged central process has the effect of lowering the efficiency of the entire system. In a sense, the damaged central process sets a limit on performance for the whole system.

If this speculation is correct, then a particular pattern of results should obtain. Subjects who have damaged or inefficient central processes should perform more similarly on all tasks because the damaged central process causes the whole system to perform inefficiently. On the other hand, those who show highly efficient central processes will be more variable on all tasks because any limitation on those tasks will be dictated by more peripheral processes, not central processes that affect the entire system. If such effects actually occur, then mental tasks including basic cognitive tasks will be more highly correlated among low IQ subjects than among high IQ subjects.

To investigate this possibility, Detterman and Daniel (1989) divided up the distribution into five equal parts. Within each division of the distribution, they correlated subtests of IQ tests with each other. They did the same for basic cognitive tasks from a battery of basic cognitive tasks. They found that correlations were as much as twice as large for low IQ subjects as for high IQ subjects. This finding provides tentative support for the idea that the origin of *g* is not in defective processes, themselves, but in the relationship of the defective processes to other parts of the system.

SUMMARY OF COGNITIVE EXPLANATIONS OF *g*

In the previous sections, I considered three possible cognitive explanations for *g*. The first is that *g* results from a single cognitive process that varies among individuals. Cognitive processes that have been suggested as a single process that could explain *g* are working memory, cognitive complexity, and speed or efficiency of processing. The second possibility is that *g* can be explained by a set of independent cognitive processes. Although no one has yet identified the specific cognitive processes that might be implicated in this explanation, there is evidence that multiple cognitive processes might explain *g*. A third possibility is that *g* is not explained by cognitive processes themselves, but rather by the relationships between processes within the cognitive system. There is also evidence that supports this position.

In general, it can be concluded that there is no single agreed upon cognitive explanation for *g*. Each of the potential explanations has some support and some negative evidence. This is a serious problem for finding a biological explanation of *g*. If we do not know how to explain *g* at the behavioral level, it will be much harder to discover the biological basis of *g*.

EXPLANATIONS OF *g* IN TERMS OF BRAIN FUNCTIONING

Now to the main topic of interest: How can *g* be explained in terms of biological processes? There must be some relationship between general intelligence and properties of the brain, but what could it be? We have already seen that there is no agreed upon explanation of *g* in terms of cognitive processes. It might be possible to find a biological explanation of *g* without ever developing a cognitive explanation of *g*. However, understanding the cognitive basis of *g* could tell us where to look in the brain or, at least, what classes of explanation might be most appropriate. Lacking an agreed upon cognitive basis of *g* means that the search for a biological basis of *g* must go forward without guidance from cognitive processes.

Given the uncertainty about the cognitive explanations of *g*, it is not surprising that biological explanations of *g* have taken a parallel route of development. In fact, as we shall see, each class of cognitive explanation has an identical class of biological explanation. Biological explanations fall into almost exactly the same categories as cognitive explanations. They include *g* explained by a single thing, *g* explained by multiple processes, and *g* explained by system characteristics.

Andrist et al. (1993) and Detterman (1994b) have reviewed the many studies that have attempted to relate brain processes to *g*. The following discussion does not repeat this information. Instead, the purpose of this discussion is to critically consider the potential for explaining *g* from each perspective.

Explanations of *g* in Terms of Single Brain Processes

There have been a number of attempts to explain *g* in terms of single brain processes. Perhaps best known of those is the work of the Hendrickson's (A. Hendrickson, 1982; D. Hendrickson, 1982; Hendrickson & Hendrickson, 1980). They developed what came to be known as the "string" measure of the complexity of evoked potentials. To obtain this measure, a string was placed to be congruent with the tracing of an evoked potential for a subject. The more elaborated the evoked potential, the longer the string would be. This unique method of measurement was combined with an interesting theory that described how errors in transmission could occur to reduce complexity of transmission (A. Hendrickson, 1982). This theory was one of neural efficiency.

In the original studies, the string measure correlated around .80 with measures of intelligence. Unfortunately, the original study had a number of methodological problems (Detterman, 1984) and subsequent efforts failed to replicate the high correlations found by the Hendricksons (Haier, Robinson, Braden, & Williams, 1984). It is interesting to note that the studies of neural efficiency explaining *g* have had a very similar course in both the biological and cognitive domains.

Another proposed explanation for general intelligence has been dendritic sprouting and neural pruning. Infants are born with a large excess of dendrites that are "pruned" during the first years of life (Huttenlocher, deCourten, Garey, & Van der Loos, 1982). This mechanism has been suggested as the possible origin of differences in *g*. Unfortunately, when persons with mental retardation are compared to those of normal intelligence, pruning does not appear to be very different (Huttenlocher, 1984) thus eliminating it as a possible explanation for *g*.

A number of other processes have been suggested as the single variable that could explain *g*. These include neural transmitters, brain size, speed of transmission, and others. Like most cognitive variables, no single biological variable has been able to reliably establish correlations with *g* that are consistently above .80 or even close to it.

Explanations of *g* in Terms of Multiple Brain Processes

Unfortunately, there is no single agreed upon model of exactly how the brain works or even what its functional parts are. However, there have been a number of techniques that have been developed that hold great potential for understanding how *g* is related to brain processes. Each of these methods has its strengths and weaknesses.

Averaged evoked potentials are recordings of current changes taken from the skull. These recordings are thought to indicate changes in brain activity. The major advantage of averaged evoked potentials is that they can record instantaneous changes in brain activity. The major disadvantage is that it is difficult or impossible to localize the exact source of the electrical activity in the brain.

Positron emission tomography (PET) can provide pictures of the functional activity in the brain. An uptake substance, such as glucose or oxygen, that has been radioactively tagged is administered to the subject. The subject then does a task of some sort during the time the uptake substance is being used by the brain. After the uptake period, the decaying radioactive material can be recorded. Those areas of the brain that were most active during the uptake period have the highest level or decaying material. It is the decaying material that is detected by the scanner after the uptake period is finished. This technique provides what amounts to a time-lapse photograph of activity in the brain during the uptake period. The advantage of this technique is that it provides very accurate estimates of activity levels of each part of the brain, because the mechanism of uptake of the tagged substances used is well known and mathematically described. The disadvantage of the method is that temporal resolution is dependent on the half-life of the uptake material used and can vary from a few minutes to more than 30 minutes. It would be impossible to identify very brief brain activity or the sequence of brain activity using PET.

Functional magnetic resonance imaging (fMRI) can also provide functional pictures of activity in the brain. This technique actually measures changes in blood flow that occur in the brain. Because blood flow takes time, the temporal resolution of fMRI is in the range of seconds and this is a major disadvantage inasmuch as many psychological processes occur in the range of milliseconds. The major advantage of this method is exceptional spatial localization of brain activity.

Both PET and fMRI have poor temporal resolution but excellent spatial resolution. On the other hand, averaged evoked potentials have poor spatial resolution but excellent temporal resolution. One suggestion that has been made is to combine these two techniques. For example, one could combine the information available from fMRI and average evoked potentials and obtain both good spatial and temporal resolution.

Both PET and fMRI have an additional difficulty. Changes in functional activity during experimental tasks must be compared to some control condition where the brain is "at rest." The active brain is then compared to the brain at rest in order to determine which areas of the brain show the greatest change in activity level. What constitutes the appropriate control condition to measure a brain at rest is not entirely clear. In some pilot work we have done, we have had subjects report thinking about all kinds of things from problems with boy friends to baseball. We have even had subjects who were falling asleep during the control condition. The control condition is an important determinant of the outcome of experiments in functional brain imaging as all such methods use subtraction to determine activity. That is, activity levels in the experimental condition are subtracted from those in the experimental condition to determine what areas of the brain were most active in the experimental condition.

Although techniques for observing thinking brains in action are most impressive and will certainly provide important information about the relationship between *g* and brain processes, the most impressive work identifying multiple parts of the brain as causing *g* comes from an older technique: brain lesions. In this technique, damage is experimentally produced in the brain by lesioning it. The results of the experimental lesion on behavioral tasks are then studied. Thomson, Crinella, and Yu (1990) systematically lesioned a large number of rats and then put them through an experimental battery of tests that was the rat equivalent of an intelligence test. They were able to identify brain areas that were most important to the psychometric *g* they identified. These areas came from different functional systems of the brain suggesting that no single functional system of the brain was responsible for *g*. These data provide strong support that multiple areas of the brain contribute to general intelligence. To what extent these findings will generalize to humans is not known.

In summary, there are numerous techniques that promise an interesting future for identifying multiple brain sources for *g*. These techniques are in the earliest stages of application and it is still not clear how useful they will be. However, there are already animal data from lesion experiments that suggest what portions of the brain may be most important to understanding *g*.

Explanations of *g* in Terms of Derivatives of Brain Processes

Interestingly, there have been few speculations that I am aware of in the neurological literature about how system characteristics of the brain might affect behavior. There is one interesting set of experiments suggesting that system characteristics of the brain may be important for understanding *g*. Haier et al. (1988) used PET to observe which portions of the brain were most active as subjects took the Raven's Progressive Matrices test. Although no particular area of the brain was implicated in solving the problems on the test when total activity level was analyzed, a counterintuitive result emerged. Subjects who had the highest IQ levels showed the lowest level of brain activity. That is, high-IQ subjects actually used less brain power than lower IQ subjects. This finding was confirmed in another study by Haier, Siegel, Tang, Abel, & Buchsbaum (1992). In this study, subjects were given a PET scan playing Tetrus, a video game. After extensive practice playing Tetrus, they were given another PET scan. As predicted from the first experiment, subjects' brains were less active during the second scan than during the first. This study suggests that the prepared, knowledgeable brain is more efficient than the less prepared, less knowledgeable brain. Evidently, there are some system organizing principles at work that make a brain more efficient.

SUMMARY OF ATTEMPTS TO EXPLAIN *g* ON THE BASIS OF BIOLOGICAL VARIABLES

In general, there have been fewer systematic efforts to account for *g* on the basis of biological variables than to account for *g* using cognitive variables. Those attempts that have been made fall into the same categories as attempts to explain *g* using cognitive variables. Like cognitive explanations, none of the biological explanations is entirely convincing as an explanation of *g*. And like cognitive explanations of *g*, they each present interesting possibilities for future research.

In some ways, attempts to explain *g* using biological variables are less impressive than explanations based on cognitive behaviors. That is probably because biological explanations require a longer inferential chain because they are more molecular than cognitive behaviors. Each biological explanation, either explicitly or implicitly, suggests a cognitive behavior that is related to *g*. Cognitive explanations of *g*, on the other hand, seldom suggest a biological mechanism. In that sense, biological explanations of *g* are often more complete than cognitive explanations.

CONCLUSIONS

There are several conclusions that can be made.

1. *g* is a scientific concept with a status much like gravity. Despite its critics, it seems a concept worthy of explanation.

2. Biological and cognitive explanations fall into three separate categories: *g* as a single thing, *g* as several things, and *g* as a derivative construct resulting from the interaction of system parts. Biological and cognitive explanations that fall into any one of these three categories have much in common.
3. None of the explanations considered here provides an entirely satisfactory explanation of *g*. None even is so plausible as to rule out other potential explanations.
4. The research done so far offers interesting possibilities for further research.

What is the best way to go about understanding *g*? In my opinion, the cognitive explanations of *g* are currently the best developed and most thoroughly researched. However, even these are none too sophisticated. Ultimately, any satisfactory theory of *g* will have to include both cognitive and biological levels of explanation. Those theories that have well-developed cognitive models associated with underlying biological mechanisms will ultimately be the most powerful. This is easy to say but hard to do. We have no adequate cognitive model of how the mind works. We have no adequate biological model of how the brain works. Our knowledge about how behavior interfaces with biology is rudimentary. Explaining *g* either in cognitive terms or in biological terms will be difficult so coming up with both cognitive and biological explanations at once will be even harder. What must be kept in mind is that *g* is, empirically, the most well-established phenomenon in the social sciences. If any social science construct is capable of explanation in either cognitive or biological terms, it should be *g*. Efforts to explain *g* are to be encouraged.

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