Intelligence and the "Personal Equation"

ALFRED A. BAUMEISTER
Vanderbilt University

Over two centuries ago astronomers, studying star transit time, noted individual differences in reaction times. This observation came to be known as the "personal equation." Despite early efforts to establish a connection between RT and general intelligence, it is only fairly recently that speed of information processing has again become a major focus as a critical element of intelligence. Much of the systematic work on this association has been conducted by Jensen. In addition to firmly establishing the relationship between RT and intelligence, Jensen has explored the role of intraindividual variability. Several generalizations can now be made: 1) average RT and standard deviation of RT are correlated, but each has a unique connection with intelligence; 2) RT and standard deviation of RT reflect the operation of different processes; 3) the more complex the RT task, the greater the influence of intraindividual variability, 4) the contribution of intraindividual variability increases as IQ decreases; and 5) there are strong neurological and genetic influences on intraindividual variability. Jensen proposed a "neural oscillation" model to explain various features of intraindividual variability. His theory blends facts uncovered through behavioral research on RT with neurological events.

Nature thrives on variability and, it seems, so do behavioral researchers. But variability means different things depending on research perspective. When we detect "noise" in data (that is, variability that we cannot or choose not to explain), we typically relegate residual natural variability to that region of darkness called "error". Depending on research strategy, what is considered error territory by some is regarded by others as the land of opportunity.

Nomothetic investigators study variability between groups using the experimental approach so that causes and effects can supposedly be specified—e.g., compare reaction times (RTs) of high and low IQ groups under two conditions of stimulus complexity. In every groups X treatment experiment there are other sources of variability, the most conspicuous of which are individual differences. Within-groups variability is a veritable nuisance to be assigned an "error term"—and then usually ignored.

On the other hand, differential psychologists consider variation among individuals of paramount concern. Here the focus is on differences arising from "natural" experiments

Direct all correspondence to: Alfred A. Baumeister, Box 154, Peabody College, Vanderbilt University, Nashville, TN 37203.

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that produce variability among individuals or groups. The spotlight is focused on individual differences, not similarities. The question "what is error?" becomes all the more interesting when the two paradigms are yoked. For instance, early intervention involves experimental manipulation of variables (e.g., day-care education) to affect an individual difference variable such as IQ. In describing inferential dilemmas faced by this type of research Spitz (1993) observed that interventionists "...have the worst of both worlds" (p. 253).

Differential researchers still must contend with another source of error variability. The "standard error of measurement" is the index of variation of an individual's scores over parallel tests. Some (e.g., Jensen, 1992) have questioned whether trial-to-trial variability is really measurement error in the conventional sense and whether, in fact, this is a phenomenon that may have important implications for intelligence theory. The classical model of reliability determination and interpretation makes certain assumptions about the nature of variability that may constrain analyses of within-subject variance.

Reliability Theory

Classical reliability theory rests on the assumption that the observed (i.e., *fallible*) score of an individual on a test is composed of two elements: *true score* and *error score* . The difference between fallible and true is error. Given parallel tests, an individual' s measurements will fluctuate because error occurs in an apparently unsystematic manner.

Aside from the assumption that fallible scores are an additive function of true and error scores, two other assumptions about true and error scores are necessary. One is that the individual' s trait is stable. The remaining assumption is that "error" is completely random and,therefore, cannot correlate with measures on any other trait, such as *g*.

Because the true score does not change, a further implication is that means and standard deviations of a distribution of true scores obtained from parallel tests will be the same across tests. Given that errors are random and normally distributed, the standard deviation of an individual' s error scores over a large (usually hypothetical) number of parallel tests will necessarily be the same as that of every other individual. Because true score is not known and, therefore, a probability distribution of true scores cannot be obtained, we conventionally calculate a standard error of measurement by multiplying the standard deviation of observed scores by the square root of $1 - r_{xx}$. Thus error probability is the same for every individual and is independent of the true score. And that is where the rub is, because there are reliable individual differences in variability across parallel tests.

This is not to say that some of the basic assumptions underlying the traditional model of test reliability have not been challenged. My purpose is to raise a different proposition. Put simply: *unreliability is reliable* and there are systematic individual differences in "error" of measurement. Furthermore, *intraindividual* variability is an important feature of intelligence.

Intelligence as Level or Variability of Performance

Intelligent behavior is usually characterized by level-of-performance—number of items correct on a test, average speed of reaction, accuracy, number of objects recalled from a display, and so on. People who are less intelligent may suffer variously from memory, perceptual, attentional, learning, information processing deficiencies, among others.

In the field of mental retardation, much experimental effort has been directed at identifying critical defects or lags.

It is well known that people with diminished intelligence, as a group, are usually more variable on many tasks. The same is also true of nonretarded children grouped by age. Of course there are instances where less intellectually able people response persevere—such as consistently choosing a particular stimulus in a two-choice discrimination task, where the reinforcement schedule (50%) may be considered adequate by that person. Nor is this to say that variability is always maladaptive—such as adjusting response patterns until an effective solution to a problem is found.

As implied earlier, interperson performance differences within groups at differing developmental levels may also have their origins in still another source of variability that is intrinsic to the individual. Reference is to intraindividual variability reflected in performance changes in parallel tests due to apparently spontaneous or transitory variations in one or more of several response attributes such as speed, latency, amplitude, magnitude, or accuracy.

Typically we collapse over trials by pooling or summing scores to obtain a composite measure of an individual' s performance. But when the task is directionally defined, by either a high or low score, then clearly consistency and level of performance are related. An individual who is inconsistent cannot achieve a good composite score, although on occasion the response may be excellent. On the other hand, high dependability does not ensure a "good" score—a person may very consistently produce a weak or poor response.

By combining measurements to obtain a representative or summative index we sacrifice vital information about individual differences in behavior—i.e., consistency and how this variable relates to other aspects of performance. The question becomes one of understanding what produced variability in the occasional high performer—a quite different question as to the conditions that prevent a second individual from ever achieving optimal performance. Two constructs are relevant: optimal performance and oscillation. Until fairly recently theorists have typically disregarded the latter. A notable exception to this generalization was and is the extensive research by Arthur Jensen on reaction time (RT) parameters, particularly intraindividual variability (Jensen, 1980; 1982; 1987; 1992; 1997).

Reaction Time

Much of the research and evidence concerning the connection between within-subject variability and intelligence has been derived from RT measures. Covariation between intelligence and RT has a long and interesting history beginning in 1796 when an astronomer found that his assistant did not agree with him in measurements of transit time and concluded that the assistant was a bit "slow". Astronomers took seriously the fact that there are consistent individual differences in RT—the *personal equation*. Later this became an important problem in psychophysics. Gilbert (1894) was apparently the first to demonstrate a reliable relationship between RT and intelligence. Most of the research on speed of information processing and its relationship to intelligence has been conducted using variations of the venerable RT task—simple, choice, memory search, and so on.

Of course, the very idea that something as complex as general intelligence could be analytically reduced to such simple tasks as RT fell into wide-spread disfavor. Correlations between RTs and measures of academic performance were evidently too low to support the contention that RT yielded a pure measure of neuroprocessing speed. Development of the Binet scales provided a much stronger predictor of school achievement than simple tasks such as RT.

Watsonian and Skinnerian behaviorism (along with Meadian culturalism) purported to show just how susceptible individual differences are to environmental interventions. Then with the rediscovery of cognitive psychology many placed bets on higher-order processes (meta-cognition) that could be trained to enable an individual to improve performance and reduce individual differences. Within contemporary behavior analytic tradition, stimulus control accounts for practically everything of behavioral significance. These positions lay claim to a certain political correctness, because if individual difference are largely the product of environmental variations they, therefore, can be rectified accordingly.

Nevertheless, the primacy of environmentalism has been challenged, particularly in recent years, for numerous reasons. These include the conspicuous failure of environmental interventions, whether broad-based early education or targeted behavior modification, to erase intellectual and social disparities and prevent or cure mental retardation. Furthermore, knowledge of biochemistry, moleculear and cyto-genetics, and brain development has increased by virtually exponential proportions. Construction of intelligence in terms of fixed structural features, including genetic and other biological determinants, began a renewed ascendancy in psychology.

Reaction Time and Intelligence. Over the years, a number of studies appeared showing that mentally retarded people are markedly slow to respond in comparison with people with higher IQs (e.g., Scott, 1940). During the 1960' s a growing body of research literature demonstrated that not only were RTs of retarded subjects slower on average, but that this disparity could be reliably influenced by numerous factors (Baumeister & Kellas, 1968b). By now one of the most firmly established correlates of intelligence is RT (e.g., Jensen, 1982, 1987, 1988, 1992). According to Vernon (1987) the resurgent interest in RT and its relation to intelligence "...may be regarded as one of the great comebacks in psychology..." (p. 1).

Given a phenotypic association between intelligence and information processing rates, questions must inevitably be raised about the nature of this relationship. Environmental influences may be implicated, despite findings that genetic variation contributes to both individual variations in general intelligence and measures of information processing speed (Vernon, 1989). The view has been expressed that the RT-IQ relationship arises from sharing of a common knowledge base, that the relationship is acquired and is specific, not general (Ceci, 1990). Furthermore, the case has been made that because many *g* tests are timed the correlation may be spurious. This argument does not stand up to the results of various studies involving time and untimed tests (Vernon, 1987).

The Biological Connection. There is a biological connection between variable speed-of-information processing and intelligence. Studies of brain-event-related potentials (ERP) or brain-evoked-potentials (AEP) lead to the conclusion that people with higher IQ scores generally have higher amplitude responses and shorter latencies, with less variability in ERPs or AEPs. These conclusions are supported by dozens of studies ranging from passive stimulation to more cognitively demanding tasks such as inspection time and memory scan (Deary & Caryl, 1991; 1997). Others (Jensen, 1992) have found that rapid RT responses are associated with certain characteristics of evoked potentials, particularly amplitude and latency.

Peripheral nerve conduction speed also shows a small but reliable correlation with psychometric *g*, although peripheral nerve conduction rate does not correlate highly with RT. There is indication that this association is mediated entirely by common genetic factors (Rijsdijk & Boomsma, 1997). The notion of greater "neural efficiency" among higher IQ subjects has some tentative support from functional brain scan studies showing that cerebral metabolic rates of people with higher IQs are lower (as contrasted with people of lesser intelligence) during periods of active information processing.

The genetic contribution to the correlation between RT and IQ was investigated by Baker, Vernon, and Ho (1991) who assessed performance on 11 RT measures among monozygotic and dizygotic twins for whom they also obtained verbal and performance IQs. They found no environmental effects in the RT-IQ association. These findings support other studies showing that hereditary factors account for much of the RT-IQ correlation, although there appear to be differences depending on which RT measure is used. Those involving symbolic processing are impacted more by environmental factors, as might be expected.

Nevertheless, evidence supporting the connection between biological indices and the RT-IQ association is open to a number of metatheoretical constraints, not the least of which is direction of causality. As Nettelbeck and Wilson (1997) have observed, there is more to RT than biological neural efficiency. These findings do not explain how cognitive performance differences are linked to genetic and neurological events.

Intraindividual Variability in Reaction Time

In reviewing the history of RT research Jensen (1992) noted a "peculiarly neglected phenomenon": variability of a person's RTs over a large number of trials. He observed that intraindividual variability has only relatively recently become a major focus of interest in differential psychology owing to two now well-established empirical facts "discovered surprisingly late" (Berkson & Baumeister, 1967). First, trial-to-trial variability in RT is not measurement error in the traditional sense and this source of individual difference is robust. Second, individual differences in intertrial variability is generally a better predictor of *g* than measures of central tendency, and that, at the very least, within-subject dispersion should be used along with averages to compare different groups on speed measures.

These considerations taken together with what was admittedly a very scant database, led Baumeister (1968) to hazard the hypothesis: "...factors related to spontaneous within-subject variability contribute more to the performance of retardates than of normals" (p. 478). Since then Detterman and Daniel (1989) found that intercorrelations among subtests on the WAIS increase as intelligence decreases, suggesting that the general factor is stronger for less bright people. From this, it follows that to the extent intraindividual variability is related to general intelligence, the influence of the variability variable should be greater among less intellectually competent people.

As Jensen has repeatedly demonstrated, this generalization applies over the full range of intelligence, not just extreme group comparisons. The fact that normal individuals of relatively low intellectual aptitude are more variable in virtually all RT tasks has also been

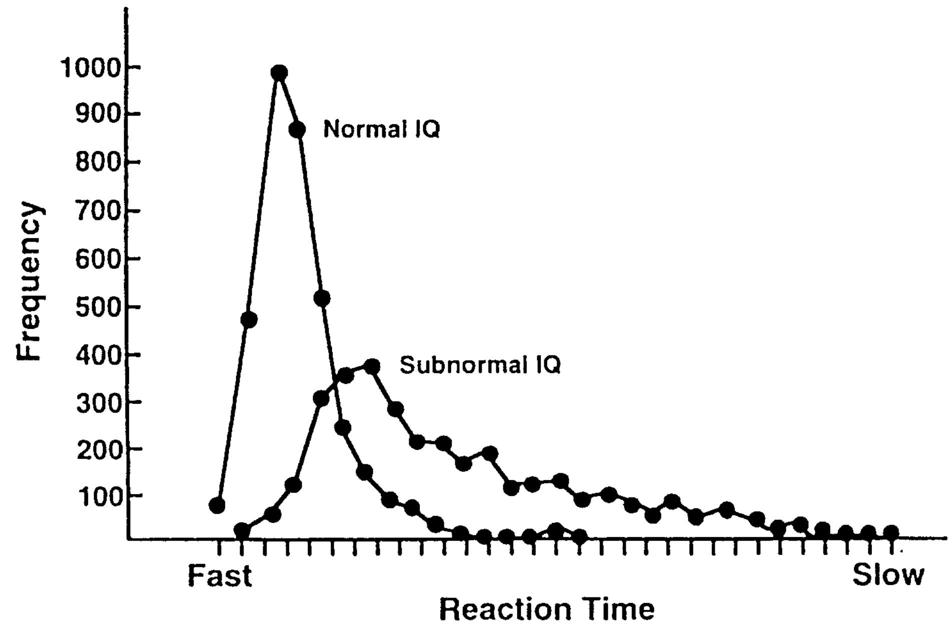

Figure 1. Distributions of reaction times of individuals with normal and subnormal IQs

repeatedly confirmed. But when one examines individual RT distributions, there is more to this relationship.

As noted earlier, on some trials people with diminished intelligence (even those who are mentally retarded) will produce a response that is nearly as fast as much brighter subjects. The RT frequency distributions of less intelligent individuals are flatter, more spread out, and skewed. Figure 1 shows typical simple-RT distributions (600 trials) for 6 college students and 6 moderately mentally retarded individuals (adapted from Baumeister and Kellas, 1968a). (These are grouped data that obscure individual differences.)

Standard deviations calculated for each individual showed no overlap between intelligence groups. But this standard deviation itself is a global score derived from hundreds of separate RT trials, and should be further decomposed.

Examining distributions in Figure 1 suggests that each may contain distinctly different populations of responses. There appears to be an underlying RT distribution with low variability. For both groups, but especially for the mentally retarded subjects, another highly variable response distribution may reflect the operation of underlying neurological oscillatory processes or, at a behavioral level, attentional drift or motivational lags. It is in regard to this second distribution that conditions inherent in mental retardation (or intellectual differences, more generally) display themselves most prominently.

Similar reasoning was expressed by Larson and Alderton (1990) who suggested that the distinguishing feature of such curves among persons with low intelligence lies in the right skew of the distribution—what they called a "worst performance rule". They maintained that the slowest RT trials are more revealing about intelligence than other aspects of the distribution. By partitioning response latencies into "bands" from fast to slow, they found that the slowest bands were the most prominent feature of intraindividual variability and were "by far" the best predictors of intelligence (and, not incidentally, working memory). Using the same procedure, but with different RT tasks, Kranzler (1992) not only observed the same pattern, but that the rank-order RT bands correlate higher with *g* for more complex tasks.

It is worthwhile to consider developmental changes in these RT attributes. We know that there is an age-related decrease in average RT, RT within-groups variability, and RT intraindividual variability up to late adolescence, and that rate of this decrease is a function of task complexity (Jensen, 1992). How early can these attributes be determined and are they enduring longitudinally?

The most convincing data regarding stability of RT from early infancy to childhood and predictability of child IQ were presented recently by Dougherty and Haith (1997). Infant RT correlated -.29, -.47, and -.44 with verbal, performance, and full-scale IQs, respectively. But of particular interest here is their finding that infant RT standard deviations correlated -.40, -.41, and -.46 with later verbal, performance, and full-scale IQs. Whereas infant RT was not a significant predictor of verbal IQ, the standard deviation was.

The Generality of Interperson Variability

Speeded tasks, especially variants of RT, lend themselves extremely well to the study of intraindividual variability and intelligence. Among their numerous attributes is that many measures can be obtained on the same individual and that systematic reactive factors, such as warm-up and fatigue, can be isolated and controlled. These tasks permit myriad variations enabling separation of input, central, and motor processes.

Nevertheless, there are questions as to 1) whether other kinds of tasks yield a similar picture of the variability-intelligence connection and 2) the extent to which variability is a more general characteristic of an individual. As Detterman (1987) has pointed out, no matter how convincing and consistent are results obtained from RT tasks, in order to establish convergent and discriminant validity, we must look to other measures. Is there a common intraindividual variability factor that extends over tasks? To be sure, speed of information processing does cover a considerable number of important events—from sensation to response output. But that obviously cannot be all there is to intelligent behavior.

Speed and Accuracy. As tasks become more complex, speed generally transforms into accuracy. Subjects may selectively or strategically increase encoding time to achieve more accurate scanning. Furthermore, there is evidence that allocation priorities vary between groups of differing general ability (Maisto & Baumeister, 1984).

Although both average RT and standard deviation of RT are correlated with *g*, directionality of effect is an issue in that intelligence may control speed, not the other way around. Consistent with this notion is the possibility proposed by Nettelbeck and Brewer (1981), that the more variable and, consequently, slower average RTs among less intellectual capable individuals are due to a general impairment of cognitive executive or metacognitive functions—a rather nebulous concept that sounds suspiciously like *g*. In consideration of results from various investigations of the speed-accuracy trade-off, it is certainly plausible that some portion of individual differences in average RT may be the product of strategies that are learned, as Nettelbeck and Wilson (1997) have suggested.

The most thorough investigations of efficiency and the speed-accuracy trade-off and its relationship to intelligence have been conducted by Brewer and Smith (1984; 1990). Using a choice RT task, they administered hundreds of trials to individual subjects. This enabled computation of conditional effects based on trial-to-trial analyses of when errors were or were not made. The importance of this method for investigation of within-subject variability is that it allows tracking of regulatory processes in information processing. Results of these studies indicate that intelligence-related differences in processing speed are the result of structural features that mediate speed, accuracy, and variability.

Other Data Bearing on the Intraindividual Variability Hypothesis

Studies utilizing other psychophysical tasks have also been reported showing that intra-subject variability is related to intelligence and age group differences. Dugas and Baumeister (1968) obtained multiple measures of auditory difference limens (DLs) and constant errors (CEs) for groups of people with normal and sub-normal intelligence. As expected, DLs and CEs differed between intelligence groups. But, as in the case of RT, standard deviations of DL and CE computed for each subject were higher among the less intellectually competent group and correlations between means and standard deviations were higher for the retarded subjects.

In another study involving DLs for pure-tone stimuli, Laine and Baumeister (1985) compared 2nd, 4th, and 6th graders and mentally retarded and normal adults (well, college students). A distinct age gradient of standard deviations of DL was observed. Mentally retarded adults fell between the 2nd and 4th grade subjects. Retention intervals varied from 1 to 10 seconds. An interaction was observed in that less intellectually mature subjects (children and mentally retarded adults) showed increased intraindividual variability with increasing retention intervals, while the normal adults did not. Again, the variability-development index predicted a specific behavioral attribute—in this case, short-term memory.

Because classical psychophysical techniques, such as the method of limits, do not allow separation of response biases from perceptual aspects of performance, Laine and Baumeister (1985) conducted a second experiment of pure-tone discrimination using signal detection methodology. Three groups were compared: 3rd graders of average IQs, college students, and mentally retarded adults. On the sensitivity measure (d') there were differences between the three ability groups in the order: college students, children, and mentally retarded adults, with sensitivity decreasing over retention intervals for all groups. Intraindividual variability is partly reflected in perceptual sensitivity that changes with developmental status. Use of auditory stimuli that are not of a phonologic or semantic nature in these studies presumably minimizes specific language-based strategic utilization.

These studies, along with some others involving motor learning and verbal learning, indicate that not only are there reliable intraindividual differences related to intelligence, but that this phenomenon is probably a general individual expression that operates at a very basic level (perhaps stemming from variability in rates of sensory, central, and motor nerve conduction). To my knowledge no study has been reported in which measures are obtained on the same individuals across different tasks, other than timed performance, that yield measures of intraindividual variability in order to determine whether there is a general factor of consistency. Questions remain concerning the importance, generality, and genesis of intraindividual variability.

The Meaning of Intraindividual Variability

Additional issues must be addressed in consideration of the source of intraindividual variability and whether this variable has an independent role in relation to general intelligence. For one thing, as noted earlier, the individual' s variability in RT contributes to RT.

A biologically determined lower limit governs the absolute speed with which an individual can respond to a signal. If the lower limit is biologically set, the upper limit is infinite (at least theoretically). RT and the standard deviation of RT are, in fact, highly correlated and both are correlated with measures of intelligence. Does this mean that they are derivatives of a common underlying neurological process and therefore are redundant? (In this regard it is important to note that the correlation between RT and standard deviation of RT is not perfect, even after correcting for attenuation.) Do they associate with different components of intelligence? How independently reliable are these measures? Related to these questions is the consideration that in most studies average RT and standard deviation of RT are not experimentally independent because they are usually obtained from the same trials. Thus their high positive correlation could be spurious. These are issues that have been addressed by Jensen, applying sophisticated analyses to large data sets from a number of RT studies (Jensen, 1992).

Consider first the question of reliability. Using a split- half reliability, odd and even trials, Jensen has found that median RT is much more reliable than the RT standard deviation. This finding leads to an interesting question: what is the meaning of the reliability of a variability measure derived from separating parallel tests into two sets? That is, if the standard deviation of RTs on odd trials is not the same as the standard deviation of RTs on even trials, cannot this variability be taken as simply another index of the same process that accounts for differences between odd trials and between even trials? Nevertheless despite its lower reliability, the RT standard deviation is usually a better predictor of general intelligence than median RT, especially in those tasks that require more complex processing.

Another finding derived from analyses of large data sets, crossing different RT paradigms, is that although median RT and standard deviation of RT share a common factor, they also contribute unique variance. They are separately correlated with *g*, reflecting different independent processes (Kanzler & Jensen, 1991). Jensen has conducted a large assortment of RT studies using the Hick paradigm (1987). He states "with considerable certainty" (p. 135) that variability and average performance behave very differently, at least with respect to Hick' s Law. Evidence from other studies, discussed previously, supports this observation. Furthermore, there are different patterns of interactions of median RT and standard deviation of RT associated with age, sex, and racial differences, again indicating that these two RT indices mirror the operation of different processes.

The Mechanisms

Referring to the extensive RT data, there are several empirically supported facts to be considered: 1) average RT and standard deviation of RT are correlated, but not perfectly; 2) both variables are correlated with *g*, but independently 3) they reflect operation of different cognitive processes; 4) there are reliable longitudinal effects of both variables, 5) genetic and neurological effects mediate the correlation between both variables and *g*; 6) average RT and standard deviation of RT have different interactive effects, depending on certain group characteristics such as age and race; 7) manipulated variables do not affect the variables in the same way; 8) some data using other measures, such as signal detection, support the contribution of consistency to intelligence; 9) the more complex the RT task, the greater the contribution of intraindividual variability; and 10) the contribution of within-person variability increases as IQ decreases.

A number of researchers have speculated as to the causal mechanisms involved (e.g., Eysenck, 1987; Nettelbeck & Wilson, 1997). The explanatory range is from higher level cognitive processes to very basic neurological events. The one who has approached the issue of causal modeling most systematically is Jensen (1980; 1982; 1987; 1992; 1997).

In view of the facts summarized above, Jensen makes the case, within his "neural oscillation" model, that two sets of explanatory mechanisms are necessary—one for speed and another for consistency. Going beyond these issues, Jensen maintains that the most heuristic approach to understanding individual differences in intelligence is to be found in research on neurological events, less in terms of brain structure per se and more in terms of molecular neurochemical and electrophysiological processes. In a recent review of the neurological bases for psychometric *g* Jensen persuasively reasons that the next generation of important advances in research on intelligence will come from the neurosciences in which elementary process components, such as consistency, are addressed through new technologies. He places his bets on brain physiology and chemistry, an eminently reasonable inference.

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