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Eliminating the IQ–RT Correlation by Eliminating an Experimental Confound

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Three experiments investigated the relation between visual scanning demands, reaction time (RT), and psychometrically defined intelligence (IQ). Prior studies have shown reliable correlations between RT and IQ in the range of −.20 to −.80. However, these studies have confounded the number of possible stimuli (stimulus uncertainty) with the size of the area in which the stimuli may appear (visual angle). Experiment 1 replicated these studies retaining this confound. As the number of stimuli increased from one to eight, the visual angle was permitted to increase as well (from 0° to 30°). The results showed that RT varied in accord with Hick's (1952) law, and a median correlation between IQ and six RT parameters (subjects' mean RTs and standard deviations at three levels of stimulus uncertainty) of −.47 was observed. Experiment 2 removed the confound, varying only stimulus uncertainty, and the median IQ–RT correlation declined to −.02. Experiment 3 held stimulus uncertainty constant at 1 bit (two stimuli) and varied visual angle; a median correlation of −.19 was observed. It was concluded that many of the previously reported correlations may not have hinged on speed of information processing alone, but at least in part on subjects' abilities to scan the display across which the stimuli appeared.

When, over a century ago, Galton (1869) sought to base intellectual attainment in simple perceptual-motor indices, he was unsuccessful. Subsequent attempts to follow through on Galton's project were deemed failures as well. Consequently, Galton's approach to the analysis of intelligence was largely abandoned in the face of the success of Binet's approach, grounded in complex higher level cognitive skills such as problem solving. Yet, during the past decade, a growing body of research has appeared that is more closely aligned with Galton than with Binet, focusing on the relation between psychometric intelligence (IQ) and measures of reaction time (RT), the latter derived from various simple laboratory tasks in the information-processing tradition.

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Typically, the Wechsler Adult Intelligence Scale (WAIS; Wechsler, 1981) or the Raven Advanced Progressive Matrices (Raven, 1938) test has been administered to subjects, and their RTs have been obtained from various experimental procedures. The list of these procedures includes the paradigms developed by Hick (1952; modified by Jensen & Munro, 1979), by Posner (Posner, Boies, Eichelman, & Taylor, 1969), and by Sternberg (1966), among others. Researchers working in the area have characteristically accounted for individual differences in RT on these *speed of information processing* (SOIP) tasks (Jensen, 1987) in terms of individual differences in "mental speed" (Vernon, 1987), a psychological concept meant to reflect either neural conduction or transmission time.

Because of the apparent simplicity of the SOIP tasks, researchers exploring the relation between RT and IQ generally have assumed that such tasks, where asymptotic performance is quickly approached, are unlikely to be affected either by learning or by cognitive strategy. Thus, RT has been viewed primarily as a reflection of a characteristic of the neural substrate (mental speed). To draw an analogy, researchers have modeled the performance of subjects on the functioning of a computer wherein the machine (the hardware) is controlled by a specified set of operations (the software, or program). Two machines running the same program can differ consistently in performance on a given task only in terms of processing time, and only then if their hardware operates at different speeds. Again, because of the apparent simplicity of the tasks, researchers have assumed that their subjects are like a group of computers all using the same program. Thus, reliable individual differences in RT can be considered to be the result of differences in the speed with which subjects' hardware can execute some or all of the operations comprising the program used to perform the task. It then follows that any correlation between RT and IQ can be attributed to mental speed.

The Jensen Paradigm: Methods and Findings

The predominant, and arguably the simplest, paradigm used for exploring the relation between RT and IQ was developed by Jensen (Jensen & Munro, 1979). Based on Hick's law (Hick, 1952), which states that RT increases linearly as a function of the $\log_2$ of the number of possible stimuli (bits of stimulus uncertainty or the number of binary choices required to reduce stimulus uncertainty to zero), Jensen designed an apparatus and a set of procedures to test subjects' SOIP abilities. Inasmuch as Jensen's methods have been described in detail elsewhere (Jensen, 1987; Longstreth, 1984), only the essential points will be touched on here. Consider first the apparatus, which is shown in Figure 1. This consists of a 33 cm × 43 cm panel with a "home" button in the lower center. Equally spaced and arranged in a semicircle around the home button are eight response buttons.

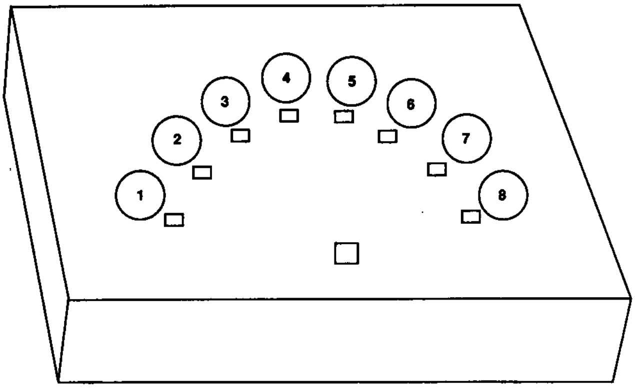

Figure 1. The layout of the response box apparatus used in the decision time (DT)/movement time (MT) studies, as described by Jensen (1987).

The radius of the semicircle is 14 cm. A small lamp (1.25 cm in diameter) is located 1.25 cm above each button.

The task is a simple one. Each trial begins with the subject holding down the home button with an index finger. A warning sound indicates that one of the small lamps will shortly be lighted. Once the lighting of a lamp is detected, the subject is to move his or her finger as quickly as possible from the home button to the response button adjacent to that lighted lamp. Other panels are fitted over the basic panel to mask out some of the lamps when conditions with different numbers of lamps (1, 2, 4, or 8) are required. The number of unmasked lamps therefore corresponds to the number of bits of stimulus uncertainty (0, 1, 2, and 3, respectively).

Jensen distinguished between decision time (DT; the time between the lighting of a lamp and the subject's release of the home button) and movement time (MT; the time between the release of the home button and the pressing of the correct response button). DT is said to represent the time required by the subject to identify the stimulus and program the response. MT is thought to reflect the time necessary for the execution of the preselected response. In a review of the research that employed his apparatus, Jensen (1987) found that the group data from 27 studies conformed to Hick's law. That is, DT increased linearly as a function of bits of stimulus uncertainty, thus supporting the idea that the procedure was measuring SOIP.

Jensen (1987) and others (Carlson & Jensen, 1982; Smith & Stanley, 1987; Vernon, 1981) concluded that SOIP, as measured by the Jensen procedure, is at least moderately predictive of IQ. The most consistent finding has been that DT is correlated negatively with IQ in all four of the bit conditions (0, 1, 2, and 3). According to Jensen (1987), the correlations have averaged −.19, −.21, −.24, and −.26, respectively. That is, subjects who score relatively high on IQ tests tend to have faster DTs than their lower IQ counterparts. Additionally, the strength of the correlation between DT and IQ frequently (but not always; see Detterman, 1987) was found to increase with task complexity, as defined by bits of stimulus uncertainty (Jensen, 1987, p. 161).

Though not supported by all studies, an additional claim was made that individual differences in slope across bit conditions also are negatively correlated with IQ (Jensen, 1987, p. 152). Thus, not only are subjects with higher IQ scores said to be relatively faster than those with lower scores, but their speed advantage is said to grow with increased processing demands. This is an important claim because the slope of the regression line across bit conditions can be viewed as the purest measure of an individual's mental speed in that it is theoretically free of individual differences regarding perceptual speed and the time required to prepare a response. These other processes are understood to be constants across the conditions, thereby affecting only the intercept of the regression line. In contrast, the slope across the conditions is sensitive only to what is different across the conditions: in this case, the number of bits or binary decisions to be made. Returning to the computer analogy, input/output (I/O) functions such as perceptual speed and the time required to prepare a response can affect mean RTs within each condition and the intercept of the regression line across conditions. But, because these I/O functions are common across tasks, they are deemed to have no effect on the slope, which, given that all subjects are using identical programs, will be sensitive only to the speed of the subject's hardware (mental speed). Finally, of all the SOIP parameters, intraindividual variability in speed, as measured by the standard deviation of DT, has been said to be the strongest predictor of IQ (Jensen, 1987; Vernon, 1987).

Longstreth's Criticisms of the RT–IQ Studies

Jensen and others who have used his apparatus and procedures have assumed not only that subjects are all using the same program, but that other factors that may influence RT parameters either randomly affect subjects or are inconsequential. Though it is possible that the apparatus and procedures provide uncontaminated estimates of mental speed, some researchers are not convinced that this is the case. Most notably, Longstreth (1984) has argued that Jensen's apparatus and procedures may not produce DT measures and slopes as analytically pure as has been assumed. This empirical criticism has direct theoretical implications. Longstreth's research suggests that the correlations obtained between IQ and the RT measures derived from Jensen's apparatus and procedures may be explainable in terms other than mental speed.

In essence, here is what Longstreth has argued. The standard procedures in studies using Jensen's apparatus have confounded the number of bits of stimulus uncertainty (bits) with the amount of practice subjects received. All subjects were tested on the conditions in an ascending order, from 0 bits to 3 bits. Consequently, either individual differences in mental speed or differential practice effects could have produced the correlation between slope and IQ (Longstreth, 1984; Widaman & Carlson, 1989). Furthermore, was it the cascading mental speed advantages or the accumulation of differential practice effects that was responsible for the often-found increasingly strong correlations in the 1-, 2-, and 3-bit conditions? Thus, an alternative theoretical interpretation could be that more intelligent subjects are those who derive greater benefit than their less intelligent cohorts from each trial: Intelligence may be related to rate of learning, not mental speed. This hypothesis, of course, has a long tradition behind it (cf. Gagne, 1967).

Longstreth (1984, p. 149) also raised the problem of possible response-bias effects. If the movements required by the various button positions required differential preparation times, then mean RTs across bit conditions would have been differentially influenced by these response preparation times. This possible confounding could exist only because the specific response buttons were not equally probable in all bit conditions. For example, Buttons 4 and 5 in Figure 1 were used in the 1-, 2-, and 3-bit conditions, whereas Buttons 1 and 8 were used only in the 3-bit condition. Consequently, if RT is sensitive to response preparation, then the slope across bit conditions may also reflect differences in response programming time, not merely the time required by the subjects to make 0 to 3 binary choices. Jensen's (1987) response to this criticism was that any such response bias, if in fact it exists, would merely attenuate the correlations with IQ. If he is correct, elimination of this confounding should strengthen the correlation between slope and IQ.

Finally, in the standard procedures used with Jensen's apparatus, bits of stimulus uncertainty has been confounded with the degrees of visual angle separating the locations of possible stimuli (visual angle). In the 0-bit condition, where only one lamp is used, the point in space where the stimulus will appear is fixed. In the 3-bit condition, where all eight lamps are used, it has been estimated that subjects were required to scan approximately 30° of visual angle from the lamp on the extreme left to the lamp on the extreme right (Longstreth, 1984, p. 146). As argued by Detterman (1987) and others, the way in which subjects search for stimulus onset could have a significant effect on RT. The question arises, then: Could the speed with which subjects were able to search the visual field have been at least partly responsible for DTs and slopes correlating with IQ? In response to such concerns, Jensen and Vernon (1986) argued that such confounding and its effects could only add noise to the RT data, thus attenuating the correlations with IQ.

Some investigators have viewed Longstreth's methodological criticisms from another perspective and consequently have reached contrary conclusions. To these investigators, practice, response bias, and the confounding of bits of stimulus uncertainty with the degrees of the visual angle were seen as sources of noise that have attenuated the RT–IQ correlation, instead of as confounding variables that might explain the observed correlation. In support of this position, Neubauer (1991) found that after eliminating possible practice effects and also reducing the likelihood of any consequences from response bias and from varying the visual angle, the correlations among RT, slope, and IQ actually increased.

Isolating the source (or sources) of variability on the RT tasks and determining the degree to which they are responsible for the correlations with IQ is crucial for theory development and the guiding of future research. Although there have been several attempts to examine the effect of visual angle on RT measures and their correlations with IQ, none of these studies has completely unconfounded bits of stimulus uncertainty and visual angle. It was this issue that motivated the following series of experiments. If the confounding of visual angle with bits of stimulus uncertainty adds only noise to the RT measures, as Neubauer (1991) suggested, then eliminating the visual angle confound from the tasks should strengthen the correlations between those measures and IQ. If, on the other hand, holding visual angle constant attenuates the correlations, then doubt is cast on mental speed interpretations of RT measures derived from the type of apparatus used by Jensen. Though not all evidence supporting the mental speed hypothesis has been derived from Jensen's paradigm, its apparent simplicity has limited the alternate interpretations. As stated by Jensen and Vernon (1986), "it seems the simplest chronometric task in terms of its minimal cognitive demands and the absence of any content that could be called 'intellectual'" (p. 155). Should the RT–IQ correlations essentially disappear with the removal of the visual angle confound, then an important source of support for the mental speed hypothesis is called into question.

EXPERIMENT 1

This first experiment constituted a replication of the studies that have used Jensen's apparatus and procedures. Degrees of visual angle, the order of presentation of the conditions, and bits of stimulus uncertainty were intentionally kept confounded. As in all of the studies that have used Jensen's apparatus, there was a high degree of compatibility between the stimuli and their corresponding responses. However, where studies employing Jensen's apparatus have required a motor response, the present series of experiments required the subjects to respond verbally. And, whereas Jensen and others have measured both DT and MT, all three experiments reported in this article measured only the time from the onset of the stimulus to the initiation of the verbal response (RT). An explanation of the motivation underlying these two changes is warranted before proceeding.

According to Jensen and Munro (1979), the use of a home key was a methodological advance because it allowed DT, which includes the time required for the completion of the relevant cognitive operations, to be separated analytically from MT, which theoretically does not contain any "cognition time." That is, it allowed RT to be decomposed into two independent parts: (a) DT, the time the subject required to detect a stimulus, identify it, and program the appropriate response (SOIP); and (b) MT, the time necessary for executing the response, an I/O function. However, several problems associated with the use of a home key have since come to light. As argued by Rabbit (1985) and Welford (1986), an error in stimulus identification or response programming can go undetected in studies employing Jensen's apparatus because the mistake can be corrected by the subject during his or her response.

There is a further problem. The use of the home key also allows for the possibility of different strategies—or programs—on the part of the subjects. Nettleback and Kirby (1983) pointed out that some subjects may wait until the response has been fully programmed before lifting their finger from the home key, but others may release the home key immediately upon detection of a stimulus and complete the identification and response programming operations "in flight." In testing for the presence of these strategic differences, Smith, MacLeish, and Brewer (1984) and Smith and Carew (1987) demonstrated that there were indeed two groups of subjects, one adopting each strategy. Smith and Carew (1987) identified these strategies both statistically and experimentally. First, using a cluster analysis, they identified two distinct groups: one with long, and the other with short, DTs. Second, Carew and Smith (1987) designed a backward-masking condition in which subjects would no longer be able to perceive the stimulus after releasing the home key. When compared with their performance in the normal condition, the DTs of some, but not all, subjects became significantly longer. It can be assumed that these were subjects who had previously been releasing the home key upon detection, but prior to identification, of a stimulus. Thus, when Jensen's apparatus is used, what is reflected in the DTs of some subjects may not be what is reflected in the DTs of others.

In light of these problems with decoupling DT from MT, Smith (1989) suggested using total RT: the duration from onset of the stimulus to pressing of the response key, the traditional measure in most cognitive studies that examine mental processing time. Furthermore, as already mentioned, Longstreth (1984, p. 149) demonstrated that if the different movements required by Jensen's apparatus required different preparation times, then the differences in both DT and MT across set size would be differentially influenced by the preparation times. To rectify this problem, Longstreth recommended designing a task that utilized highly similar responses, and then analyzing only those responses common to all set sizes.

To respond to both of these problems, the following two methodological strategies were used in all three experiments reported here. First, to avoid the potential problems associated with the use of a home key, a verbal response was required of the subjects, and RT was measured from the onset of the visual stimulus to the initiation of the response. Because the names of each of the stimuli used in these experiments (the colors red, blue, green, and white) began with a different consonant, the probability of the initiation of an incorrect response going undetected was quite low. Second, any response-bias effects were avoided by having all stimuli appear with equal frequency in all conditions. Although there may have been differences in response-programming time for each color, there would have been no differences in the average response-programming time across conditions.

Method

Subjects. The subjects were 36 university students (23 women and 13 men) who were given extra credit in an introductory psychology class for their participation. Those potential subjects who had not had their vision tested in the past year were tested with a Snellen letter chart. As in the other two experiments reported here, individuals who failed to test 20/20 (corrected) were excused from the study. No subjects in this study took part in more than one of the experiments.

Apparatus. Both stimulus presentation and the calculation and recording of RTs were controlled by an IBM-AT compatible computer. The stimuli were presented on a Hyundai 35.56-cm high-resolution (VGA) color monitor (HCM-421E). Responses were collected by an interfaced custom-made voice key. Machine language subroutines with millisecond accuracy calculated each RT (Graves & Bradley, 1987). Immediately following each trial, the accuracy of the response was scored by the experimenter, who sat behind and to the side of the subject holding a keyboard. This scheme remained the same throughout the three experiments.

Measure of Psychometric Intelligence. In small groups, all subjects were administered the Raven Advanced Progressive Matrices (Raven) test, usually during the same week that they participated in the experimental task. Subjects completed both the 12 practice and the 36 test items of the Raven. The standard instructions were read aloud by the examiner, and standard timing was followed.

RT Task Procedure. Individual subjects were seated in a dimly lighted room with their heads in a restraining apparatus that positioned their eyes level with, and at, a minimum distance of 36 cm from the monitor. A microphone was placed 4 cm from the subject's mouth. The instructions for each block of trials were printed on the screen and read aloud by the experimenter.

On the left side of Figure 2 is displayed the sequence of a typical trial in Condition 0, the 0-bit condition. Each trial began with an outline of a small empty white-on-black square (1 cm^2) in the middle of the screen. After a 1-s interval, the computer issued a warning beep. Then, following a variable foreperiod (1–3 s), the empty square was filled with one of the four colors (red, green, blue, or white). The changing of the square's color was accomplished using the tachistoscopic technique described by Graves and Bradley (1988). Sub-

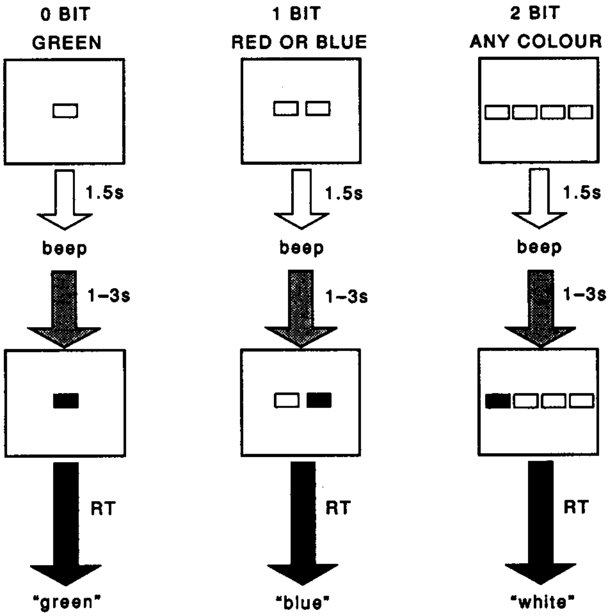

Figure 2. The sequence of events in a typical trial in Condition 0 (0 bits) on the left, Condition 1 (1 bit) in the middle, and Condition 2 (2 bits) on the right.

jects were instructed to name the color as quickly as possible. There were four blocks of 12 trials. Subjects were informed in the instructions prior to each block as to which color was to be used in that block, so that there was no color uncertainty. For example, in the first block, the subject would be told that the stimuli for all 12 trials would be red.

The middle of Figure 2 displays the sequence of events in Condition 1, which used the same four colors, but with two presented in each block of 12 trials (1 bit of stimulus uncertainty). Each trial began with the outlines of two 1-cm^2 squares, 10 cm apart, followed 1 s later by a warning beep, the variable foreperiod, and the filling of one of the squares with one of two colors. Given the subject's distance from the screen, the two locations were separated by 15° of visual angle. Subjects were told to name as quickly as possible the color that filled either of the two empty squares. Subjects were instructed as to which two of the four colors were to be used in each block of 12 trials and in which position each color would appear when it was presented. Blocks 1 and 2 used one pair of colors; Blocks 3 and 4 used the remaining pair. Though the two active colors within each block appeared with equal frequency, the order in which they were presented was random.

Condition 2 involved two bits of stimulus uncertainty, and is shown on the right side of Figure 2. Each trial began with the outlines of four equally spaced squares, 6 cm apart, appearing on the screen. Given the distance between the subject and the screen, the left-most square and the right-most square would be separated by approximately 30° of visual angle. All four colors were used in all four blocks of 12 trials. Subjects were again told which color would appear in which position. Subjects were told to watch the screen and to name as quickly as possible the color that filled one of the squares following the warning beep. All colors appeared with equal frequency in all blocks, but the order of presentation was random. In summary, subjects faced not only increasing stimulus uncertainty across conditions, but also increasing scanning demands.

All subjects were tested in all three of these conditions in ascending order, from 0 to 2 bits. Within each condition, each color was associated with only one screen position. Thus, screen position and color were redundant. This was true for all three experiments reported here. The variable foreperiod in all conditions in this experiment, as well as in the two experiments to follow, was random between 1 and 3 s. The intertrial interval varied between 2 and 4 s. If the subject's verbal response did not activate the voice key on a given trial, that trial was scored as a fault and was not used in calculations; the same was true for inadvertent activations. Subjects were given four training trials on each condition prior to testing. RT in all conditions was defined as the elapsed time from the filling of the empty square with a color to activation of the voice key. All RTs shorter than 100 ms or longer than 3 s were scored by the computer as errors.

Results and Discussion

RT Parameters Summary. Table 1 displays summary statistics for all of the measures obtained from the 36 subjects. It is particularly noteworthy that the mean Raven for these subjects was consistent with that found in other RT studies using university undergraduate students as subjects.

As can be seen from Table 1, regardless of the number of bits of stimulus uncertainty, subjects made very few errors. Error rates such as those found here have been deemed optimal for information-processing studies (Smith, 1989, p. 830). They were low enough to indicate that subjects had little difficulty with the task, but high enough to suggest that the subjects presumably were trying to go as fast as they could.

Table 1 also illustrates that the grouped data generally conformed both to Hick's law and to the findings of RT–IQ studies that have employed Jensen's apparatus. The group mean RTs showed an almost perfect linear increase across bit conditions. This was confirmed by a significant linear trend, $F(1, 35) = 210.87$, $MS_e = 3113$, $p < .001$, and the absence of any quadratic trend, $F < 1$. As bits increased, RTs tended to become more variable, illustrated in Table 1 by the standard deviations of the RTs. Though there were only 48 trials per condi-

TABLE 1
Experiment 1: Summary Statistics

Variable	*M*	*SD*	Reliability Coefficient	Correlation With Raven
Age	20.5	1.3	—	—
Raven	22.7	5.9	—	—
AC0	46.1	2.3	—	—
AC1	46.4	1.6	—	—
AC2	46.5	1.9	—	—
RT0	450	64	.92	−.31
RT1	548	75	.88	−.56**
RT2	641	91	.96	−.57**
*SD*0	62	22	—	−.39*
*SD*1	99	50	—	−.55**
*SD*2	117	50	—	−.39*
Slope	93	45	—	−.41*

Note. AC = number of correct responses of 48; RT = mean response time; *SD* = standard deviation (intrasubject variability); RT, *SD*, and slope are reported in milliseconds. The 0, 1, and 2 following RT, *SD*, and AC refer to the number of bits of stimulus uncertainty. Reliability estimates are Spearman-Brown corrected split-half (odd-even) correlation coefficients.

$^*p < .05$. $^{**}p < .001$.

tion, RT reliabilities were quite acceptably high (.92, .88, and .96). These split-half Spearman-Brown corrected reliability coefficients calculated on odd-even correct trials are similar to those reported by investigators who have used Jensen's apparatus. Table 2 displays the correlations among the RT parameters. The substantial correlations between RT0–RT1, RT0–RT2, and RT1–RT2 (.74, .53, and .87, respectively) can be interpreted as revealing a reliable individual difference across the three tasks.

TABLE 2
Experiment 1: Correlations Among RT Parameters

	RT0	RT1	RT2	*SD*0	*SD*1	*SD*2	Slope
RT0	1.00	.74**	.53**	.71**	.10	.20	−.19
RT1		1.00	.87**	.54**	.48**	.44**	.41*
RT2			1.00	.35*	.34*	.70**	.73**
*SD*0				1.00	.26	.19	−.20
*SD*1					1.00	.29	.31
*SD*2						1.00	.65**
Slope							1.00

$^*p < .05$. $^{**}p < .01$.

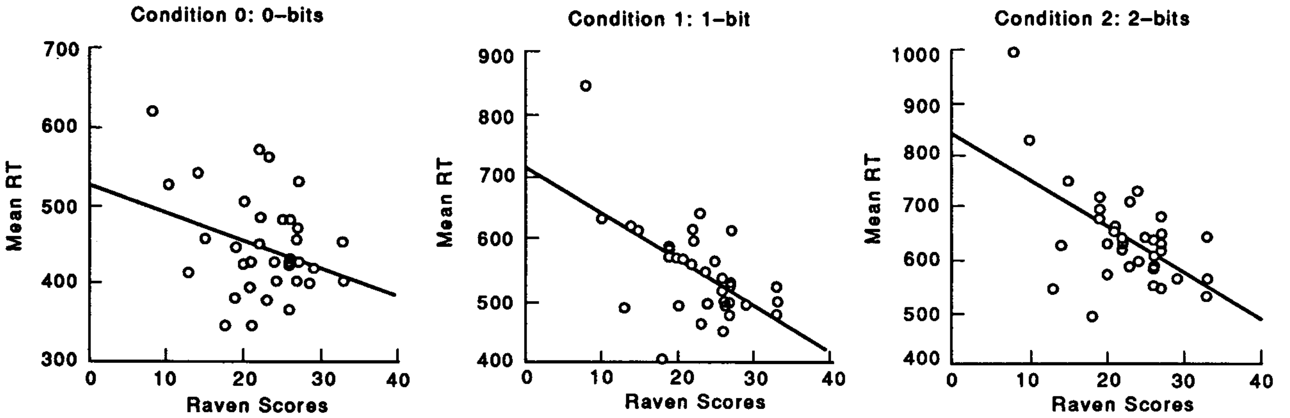

Figure 3. Experiment 1: RT regressed on Raven score.

RT–IQ Correlations. Figure 3 depicts the subjects' mean RTs regressed on their Raven scores separately for each bit condition. In all three bit conditions, there was a tendency for the subjects with the higher Raven scores to have the faster mean RTs. The right-hand column in Table 1 shows the strengths of these tendencies. In addition to the mean RTs, both intraindividual trial–trial variability (standard deviation) and slope were negatively correlated with Raven scores. In general, subjects with relatively high Raven scores tended to have faster and less variable RTs. All of these correlations are at least as high as those found in most other studies examining the relation between RT and IQ with university students as subjects.

Though the correlations between RT and Raven can be rank-ordered by bits, the lack of any real difference in correlation for the 1-bit and 2-bit conditions makes it difficult to conclude that there was a systematic increase in the strength of the relation between RT and Raven with increasing task complexity. Intraindividual standard deviation scores (*SD*0, *SD*1, and *SD*2) all correlated significantly with Raven scores, but the correlations did not increase with task complexity. It is also worth pointing out that this measure of variability was not consistently the best predictor of Raven score, in contrast to prior studies. As Jensen (1987) pointed out, given that the reliability of intraindividual variability on such tasks is typically lower than mean or median RT reliability, conclusions regarding correlations between measures of variability and IQ should be so qualified.

Finally, the theoretically important variable, slope, was significantly correlated with Raven, indicating that subjects with higher Raven scores required less of an increase in processing time with each increase in bits of stimulus uncertainty than did their lower scoring cohorts. Removing any possible response-bias effect did not appear to attenuate the correlation between slope and IQ. This is consistent with mental speed models such as Jensen's.

In summary, the apparatus, tasks, and procedures used here produced results very similar to those found in studies using Jensen's apparatus, tasks, and procedures. Although the absolute values of the RT measures are different, the general pattern of their values and their correlations with Raven scores are consistent with past studies. We are on firm ground, then, to continue our exploration.

EXPERIMENT 2

As already set out, one of the criticisms of studies employing Jensen's apparatus has been that stimulus uncertainty has been confounded with the degrees of visual angle, thus permitting alternate interpretations of the findings. Longstreth (1984, p. 147) found that the slope across bit conditions was steeper when the spatial locations of stimuli were uncertain than when they were fixed. Using Jensen's apparatus, however, Widaman and Carlson (1989) found no effect of spatial configuration. They examined the slopes resulting from Jensen's original procedure and those from an alternative assignment of stimuli within the different bit conditions. In the alternative assignment condition, the 0-bit task consisted of only the left-most lamp on the panel, the 1-bit task consisted of the left-most and the right-most lamps, the 2-bit task consisted of the left-most lamp, the right-most lamp, and those immediately adjacent to them, and the 3-bit task consisted of all eight lamps.

Though Widaman and Carlson (1989, p. 88) found no significant difference between the slopes resulting from the original and alternative conditions, visual angle effects still cannot be dismissed. In fact, their experiment did not fully unconfound visual angle and bits of stimulus uncertainty. First, the vertical distance to be scanned by the subjects in the 0-bit task was less than in the 1-, 2-, and 3-bit tasks. In the 0-bit condition, the visual angle separating the locations of possible stimuli was 0. Using Longstreth's (1984) approximation, in the 1-, 2-, and 3-bit conditions there would have been 30° of visual angle separating the left-most and the right-most locations. Second, given that the lamps on Jensen's apparatus are arranged in a semicircle, the horizontal visual angle in the 3-bit task was greater than in the 2-bit tasks, which was greater than in the 1-bit and 2-bit tasks. If visual angle is inversely related to RT, as suggested by Longstreth's (1984) research, then the slope Widaman and Carlson found in the alternative assignment condition would not have been free from the influence of visual angle, conflicting with their assumption.

Kranzler, Whang, and Jensen (1988) directly examined the effects of spatial arrangement of stimulus locations on the slope across the 0-bit and 1-bit tasks using Jensen's apparatus. In the 1-bit task, subjects were tested under both a grouped and a spread condition. In the grouped condition, subjects responded to the two lamps at the apex of the semicircle; in the spread condition, they responded to the left-most and the right-most lamps. Though Kranzler et al. (1988, p. 383) found a significant difference between the two resulting slopes (the spread condition having the steeper of the two), they dismissed its importance on the grounds that the amount of variance explained by spatial arrangement was negligible ($\eta^2 = .01$).

Upon closer inspection, however, their findings actually support rather than contradict the alternate explanation that visual angle, at least in part, is responsible for any individual differences in slope across conditions. Stimulus uncertainty and visual angle remained confounded. The 1-bit task (spread) had the greatest area to be scanned, the 1-bit (grouped) task's area was smaller, and the area in the 0-bit task was the smallest. The mean RTs for the three conditions were ordered in the same way. Thus, the results found by Kranzler et al. (1988) are what would be expected if visual angle were systematically influencing RT.

Experiment 2 was designed to completely unconfound visual angle and bits of stimulus uncertainty for the first time. RTs were collected under three bit conditions (0–2) while visual angle was held constant. If Jensen is correct—and visual angle is inconsequential—then the RTs, the slopes, and their correlations with

Raven scores should be relatively unaffected. In fact, if visual angle only adds noise to the data, then its removal should result in strengthened correlations between RT parameters and IQ, as suggested by Neubauer (1991). If, on the other hand, the confounding of visual angle is crucial to the observed pattern of results, then breaking that confound should affect the RTs and slopes, and should reduce or eliminate their correlations with IQ.

Method

Subjects. The subjects were 34 university students from the same pool as in Experiment 1 (but without overlap) who were given extra credit in an introductory psychology class for their participation (22 women and 12 men).

Procedure. The apparatus, timing, and response scoring were carried out in virtually the same way as in Experiment 1. As in Experiment 1, subjects were seated in a dimly lighted room with their heads in a restraining apparatus that positioned their eyes level with and at a minimum distance of 36 cm from the monitor. The instructions for each block of trials were printed on the screen and read aloud by the experimenter. Each trial in all conditions began with an outline of a single small square (1 cm^2) appearing in the middle of the screen followed 1 s later by a warning beep, a variable foreperiod and a color filling the inside of the square. Subjects were instructed to name as quickly as possible the color (red, green, blue, or white) that filled the empty square.

Condition 0 (0 bits) in Experiment 2 consisted of four blocks of 12 trials. Subjects were informed in the instructions preceding each block as to which one of the four colors was to be used in that block of trials. In Condition 1 (1 bit), subjects were instructed at the beginning of each block as to which two of the four colors were to be used. As in Experiment 1, two of the four blocks used one pair of randomly presented colors as stimuli and the other two blocks used the remaining pair. In Condition 2 (2 bits), all four colors were used in all four blocks.

In all conditions, subjects were told to watch the screen and to name as quickly as possible the color that filled the square. Again, all subjects were tested in all conditions in ascending order of complexity (number of colors), with four training trials on each condition prior to testing.

Results and Discussion

RT Parameters Summary. Table 3 summarizes the descriptive data on the various measures collected. Note once again that the Raven profile was very similar to that of Experiment 1 and to prior studies in this domain. As can be seen from Table 3, subjects were again highly accurate in all conditions.

By inspection, the mean RTs generally conformed to both Hick's law and the findings of other RT–IQ studies. RT split-half Spearman-Brown corrected re-

TABLE 3
Experiment 2: Summary Statistics

Variable	*M*	*SD*	Reliability Coefficient	Correlation With Raven
Age	19.9	1.2	—	—
Raven	21.1	6.3	—	—
AC0	47.3	1.0	—	—
AC1	47.2	1.1	—	—
AC2	47.2	0.8	—	—
RT0	420	63	.95	.03
RT1	523	82	.97	−.17
RT2	552	75	.95	−.04
*SD*0	55	14	—	−.02
*SD*1	77	36	—	−.01
*SD*2	69	25	—	.06
Slope	93	45	—	−.16

Note. AC = number of correct responses of 48; RT = mean response time; *SD* = standard deviation (intrasubject variability); RT, *SD*, and slope are reported in milliseconds. The 0, 1, and 2 following RT, *SD*, and AC refer to the number of bits of stimulus uncertainty. Reliability estimates are Spearman-Brown corrected split-half (odd-even) correlation coefficients.

liability coefficients calculated on odd-even correct trials again were acceptably high. Table 4 illustrates the substantial correlations among all of the RT parameters except for slope. Of particular note are the correlations between RT0–RT1, RT0–RT2, and RT1–RT2 (.91, .91, and .94, respectively), again indicating a reliable individual difference across the three tasks.

There were, however, some important contrasts between Experiments 1 and 2. Neither the within-subjects variability (standard deviation) nor the differences between the subjects' variabilities showed the same systematic increase across bit conditions as they did in Experiment 1. Also, unlike Experiment 1, the significant linear trend in RT, $F(1, 33) = 601.72$, $MS_e = 493$, $p < .001$, was accom-

TABLE 4
Experiment 2: Correlations Among RT Parameters

	RT0	RT1	RT2	*SD*0	*SD*1	*SD*2	Slope
RT0	1.00	.91**	.91**	.74**	.51**	.77**	.18**
RT1		1.00	.95**	.74**	.66**	.81**	.45**
RT2			1.00	.71**	.60**	.83**	.57**
*SD*0				1.00	.65**	.72**	.23**
*SD*1					1.00	.64**	.40*
*SD*2						1.00	.45**
Slope							1.00

*$p < .05$. **$p < .01$.

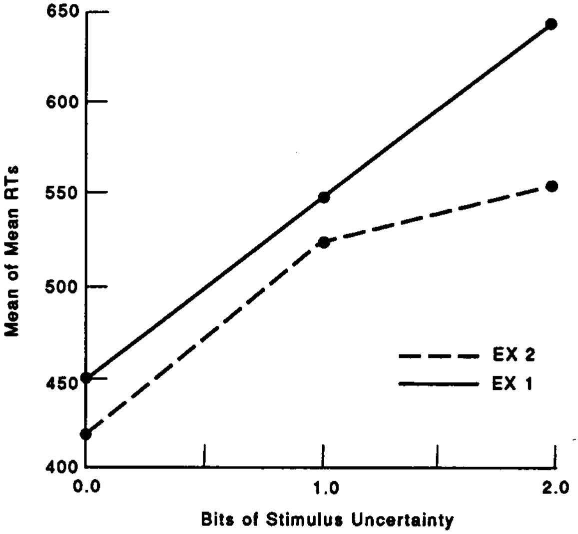

Figure 4. The differences in mean RT between Experiment 1 (with bits of stimulus uncertainty and visual angle confounded) and Experiment 2 (with visual angle held constant).

panied by a significant downward concave quadratic trend, $F(1, 33) = 61.16$, $MS_e = 501, p < .001$.

The differences between the mean RTs in Experiments 1 and 2 are illustrated in Figure 4. Subjects in Experiment 2, where visual angle was held constant at 0°, were somewhat faster, particularly in the 2-bit condition. This corresponds to the difference in the standard deviations of the RT across the two experiments. Analysis of the combined data from the two experiments revealed that, overall, subjects who had to contend with increases in scanning demands were significantly slower than those who did not, $F(1, 68) = 8.30, MS_e = 14895, p < .005$. Furthermore, a test for linear trend disclosed a significant interaction between spacing and bits, $F(1, 68) = 16.43$, $MS_e = 1842$, $p < .001$, showing that the slope of the function found in Experiment 2 was significantly flatter than that found in Experiment 1. The eta-square (.11) indicates that visual angle and the accompanying scanning demands influenced RTs substantially and cannot be readily dismissed as Kranzler et al. (1988) did.

RT–IQ Correlations. Figure 5 depicts the subjects' mean RTs regressed on Raven scores separately for each bit condition. In the 0-bit and 2-bit conditions, there was virtually no change in RTs across Raven scores. Only in the 1-bit condition was there a trend for subjects with the higher Raven scores to have the faster mean RTs. Table 3 shows the corresponding correlations. In comparison

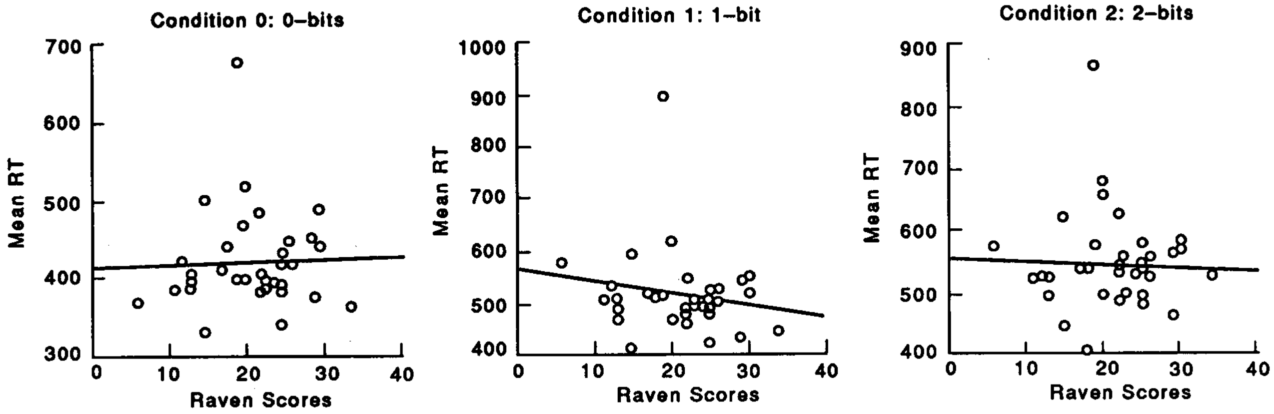

Figure 5. Experiment 2: RT regressed on Raven score.

with those found in Experiment 1, the correlations between Raven scores and mean RTs were greatly reduced, dropping to nonsignificant levels. The same was true with respect to the correlations between Raven and intraindividual trial–trial variability, and between Raven and slope. None of the RT measures correlated significantly with Raven.

The conclusion derived from the results of Experiment 1 (and studies using Jensen's apparatus) that subjects with relatively high Raven scores tended to have faster and less variable RTs on SOIP tasks cannot be drawn from the data in Experiment 2. In summary, holding visual angle constant lowered RTs and attenuated the correlations between all RT parameters and Raven scores. The removal of the visual angle confound and the reduction of scanning demands from Experiment 1 to Experiment 2 appears to have been pivotal.

EXPERIMENT 3

The results of Experiment 2 suggested that in previous studies of IQ and RT, visual angle has been at least partly responsible for individual differences in RTs, slopes across bit conditions, and the correlations between RT parameters and IQ. This third experiment was an attempt to test this conclusion, as well as to further clarify the magnitude of the effect of visual angle on RT parameters and their correlations with IQ. The impression that visual angle has been a more important factor than was previously thought would be strengthened if it was found that a task involving only the varying of visual angle produced a pattern of RTs with reliable individual differences and correlations with IQ similar to those found in studies where the number of bits of stimulus uncertainty and degrees of visual angle have been confounded. Experiment 3 tested the hypothesis: Would varying visual angle alone produce findings similar to those summarized by Jensen (1987)? To do so, bits of stimulus uncertainty were held constant and visual angle was varied.

Method

Subjects. The subjects were 48 university students (31 women and 17 men) from the same pool as the prior two experiments (without overlap). Subjects were given extra credit in an introductory psychology class for their participation.

Procedure. The apparatus, and trial sequence were the same as in the first two experiments. Again, as in the first two experiments, subjects were seated in a dimly lighted room with their heads in a restraining apparatus that positioned their eyes level with, and at a distance of, 36 cm from the monitor. A microphone was placed 4 cm from the subject's mouth. All three conditions involved 1 bit of stimulus uncertainty. In Condition 0, each trial began with an outline of a small square (1 cm^2) appearing in the middle of the screen (focal point) followed 1.5 s later by a warning beep and the square filling with color. Subjects were instructed to name as quickly as possible the color that filled the empty square. There were four blocks of 12 trials. Subjects were informed in the instructions as to which two of the four colors (red, green, blue, or white) were to be used in that block of trials. Two of the four blocks used one pair of colors and the other two blocks used the remaining pair.

Condition 1 was identical to Condition 1 in Experiment 1. Each trial began with the outlines of two squares, 10 cm apart (15° of visual angle), followed 1 s later by a warning beep, a variable foreperiod, and the filling of one of the squares with a color. Subjects were told to name as quickly as possible the color that filled either of the two empty squares. Subjects were instructed as to which two of the four colors were to be used in each block of 12 trials and in which position each color would appear when presented. The assignment of color to location was invariant across trials. Two of the four blocks used one pair of colors and the other two blocks used the remaining pair.

Each trial in Condition 2 began with the outlines of two squares, 20 cm apart (30° of visual angle), appearing on the screen. These two squares were in the positions of the left-most and right-most squares in Condition 2 of Experiment 1. As in Condition 1, subjects were instructed as to which two of the four colors were to be used in each block of 12 trials and in which position each color would show when it appeared. Two of the four blocks used one pair of colors and the other two blocks used the remaining pair. Thus, stimulus uncertainty was held constant at 1 bit (a choice between two colors) across the conditions, whereas degrees of visual displacement varied. As in Experiment 1, within each condition, each color was associated with only one screen position.

All subjects were tested in all conditions in ascending order, with 0°, 15°, and then 30° of visual angle separating the stimulus locations. As in the previous two experiments, subjects were given four training trials on each condition prior to testing.

Results and Discussion

RT Parameters Summary. Table 5 summarizes the data for the 48 subjects, who again showed the by-now standard Raven profile. The accuracy rates in this experiment were also similar to those found in Experiments 1 and 2.

What Table 5 primarily illustrates is that an increase in scanning demands, within a range approximating that found in studies using Jensen's apparatus, resulted in an RT profile similar to that found in previous RT–IQ studies that have used Jensen's apparatus. This was true despite the absence of any manipulation of bits of stimulus uncertainty. As in Experiment 2, in addition to a significant linear trend, $F(1, 47) = 85.05$, $MS_e = 1699$, $p < .001$, there was also a significant quadratic trend, $F(1, 47) = 11.89$, $MS_e = 1044$, $p < .001$, across bit conditions. The trend in this case, however, was upwardly concave. RT split-half

TABLE 5
Experiment 3: Summary Statistics

Variable	*M*	*SD*	Reliability Coefficient	Correlation With Raven
Age	20.5	1.5	—	—
Raven	22.6	5.8	—	—
AC0	46.0	2.3	—	—
AC15	46.4	1.7	—	—
AC30	46.5	1.5	—	—
RT0	533	76	.92	−.25
RT15	552	83	.95	−.13
RT30	611	85	.89	−.11
*SD*0	68	23	—	−.39*
*SD*15	82	38	—	−.02
*SD*30	146	80	—	−.25
Slope	38	29	—	.16

Note. AC = number of correct responses of 48; RT = mean response time; *SD* = standard deviation (intrasubject variability); RT, *SD*, and slope are reported in milliseconds. The 0, 15, and 30 following RT, *SD*, and AC refer to the number of degrees of visual angle. Reliability estimates are Spearman-Brown corrected split-half (odd-even) correlation coefficients.

$^*p < .05$.

Spearman-Brown corrected reliability coefficients calculated on odd-even correct trials again were acceptably high, indicating that the RTs produced by varying only visual angle were no less reliable than those produced by varying only bits or by varying both bits of stimulus uncertainty and visual angle. Table 6 displays the correlations among the RT parameters. The correlations between RT0–RT1, RT0–RT2, and RT1–RT2 were again high (.86, .75, and .79, respectively), indicating a reliable individual difference across the tasks.

RT–IQ Correlations. Figure 6 depicts the subjects' mean RTs regressed on Raven scores separately for each condition. As in Experiment 1, there was a

TABLE 6
Experiment 3: Correlations Among RT Parameters

	RT0	RT1	RT2	*SD*0	*SD*1	*SD*2	Slope
RT0	1.00	.86**	.75**	.42**	.23	.18	−.21
RT1		1.00	.79**	.40**	.50**	.10	.03
RT2			1.00	.35*	.27	.48**	.50**
*SD*0				1.00	.46**	.28	−.04
*SD*1					1.00	.14	.09
*SD*2						1.00	.48**
Slope							1.00

$^*p < .05$. $^{**}p < .01$.

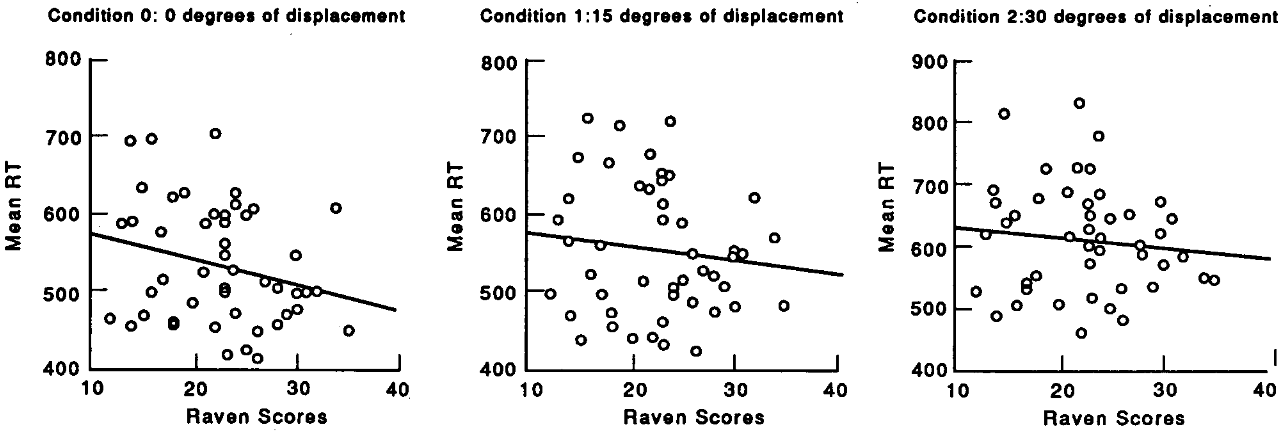

Figure 6. Experiment 3: RT regressed on Raven score.

tendency for the subjects with the higher Raven scores to have the faster mean RTs in all three conditions. The strengths of these tendencies are shown in Table 3. Although none were significantly large, the correlations between RT and Raven found here in Experiment 3 were nevertheless larger in magnitude than those found in Experiment 2, where only stimulus uncertainty was varied. The median *r*s for RT with IQ over Experiments 1 to 3 were −.56, −.04, and −.13, respectively. The same pattern was true for the correlations between intraindividual variability (*SD*0, *SD*15, and *SD*30) and Raven, save for Condition 1. Here, the median *r*s with IQ over the three experiments were −.39, −.02, and −.25. Though not as convincingly as in Experiment 1, subjects in Experiment 3 with relatively high Raven scores tended to have faster and less variable RTs than their lower scoring cohorts. Slope, however, did not correlate significantly with Raven scores as it had in Experiment 1.

Experiment 3 supports the conclusions derived from the previous two experiments in this article and calls into question the conclusion that the pattern of data reported by Jensen and his colleagues—especially the reliable correlation between RT and IQ—derives from the manipulation of stimulus uncertainty. Instead, the manipulation of visual angle appears to play a significant role. When the two dimensions are confounded, as in Experiment 1 and the bulk of the prior work using this paradigm, the widely reported pattern is obtained. When the visual angle confound is removed by holding that factor constant so that *only* stimulus uncertainty is manipulated, as in Experiment 2, the usual pattern disappears. When stimulus uncertainty is held constant and *only* visual angle is manipulated, as in Experiment 3, a pattern more closely resembling the familiar one found in studies using Jensen's apparatus reappears.

GENERAL DISCUSSION

Taken together, the results of the three experiments reported here undermine the proposition that individual differences in mental speed—and mental speed alone—have been responsible for the correlations between RT parameters and IQ in earlier studies employing Jensen's apparatus. Our findings also contradict those of Neubauer (1991), who found that reducing the degrees of spatial uncertainty (but not fully eliminating the confounding) resulted in increased correlations between RT and IQ. In the series of experiments here, when previously confounded variables were fully disentangled, it was revealed that visual angle—and likely the resulting visual scanning demands—have had more influence on RT parameters than has been acknowledged. Indeed, it appears that visual angle has made an important contribution in prior studies, confirming one of Longstreth's (1984) reservations about Jensen's RT apparatus.

An examination of the correlations between RT0 and Raven found in Tables 1 and 3 (−.31 and .03), however, appears to reveal a possible inconsistency. Formally, Condition 0 in Experiments 1 and 2 are identical. In both cases, all stimuli were presented at a single location with no uncertainty as to the color of the stimulus on any given trial. Given that these two conditions were identical, the question of the reason for the apparent difference between the two correlations might be raised. Given, at least upon initial inspection, that the removal of the visual angle confound could not have been responsible for the attenuation of the correlation in Condition 0, might not something else, such as reduced reliability or restriction in range, have been responsible for the lower correlations? When Experiment 2 is examined, however, there is no indication of reduced reliability or restriction in range. The treatment effects across Experiments 1 and 2 are comparable. The split-half reliability coefficients do not differ across the two experiments. The correlations among RT0, RT1, and RT2 are, if anything, higher in Experiment 2 (.91, .91, and .94) than they are in Experiment 1 (.74, .53, and .86). The mean and standard deviation of the Raven scores in Experiment 2 (21.1 ± 6.3) show no restriction in range in comparison to Experiment 1 (22.7 ± 5.9), nor do the standard deviations of RT0, RT1, and RT2 (Experiment 1: 64 ms, 75 ms, 91 ms; Experiment 2: 63 ms, 82 ms, 75 ms). Seemingly, the only differences between the results of the two experiments pertain to the correlations with IQ. Furthermore, it must be recalled that neither of the RT0–IQ correlations were significantly different from 0, nor were they significantly different from each other. Viewed this way, there really is nothing to be explained.[1]

The overall pattern of results reported here strongly suggests that there exist reliable individual differences in abilities to scan the visual field and that these differences have added more than simply noise to the RT parameters obtained from subjects tested on Jensen's apparatus. When the correlations between RT parameters and Raven scores in Experiments 2 and 3 are compared, it is evident that individual differences in the ability to deal with the size of the visual field in which stimuli may appear was a better predictor of IQ than bits of stimulus uncertainty, and probably considerably better. Furthermore, there is reason to suspect that differences in handling visual angle are grounded in strategic (software) differences rather than in hardware differences. In fact, given previous findings concerning strategic differences in scanning between mentally retarded and normal subjects, Detterman (1987, p. 195) argued that "it would seem unlikely that search strategy in choice reaction time would not vary across IQ levels."

There are at least two general implications for future research that arise from these three experiments. The first regards further attempts to explore the relation between choice RT measures and IQ. The notion that elementary information-

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[1] The correlations between RT1 and Raven found in Tables 1 and 5 do reveal an inconsistency. Again, though, there are no indications of reduced reliability or restriction of range in Experiment 3 relative to Experiment 1. The only difference is the strength of the correlations between RT1 and IQ. In this one case, using Fisher's test, the two correlations were found to be significantly different ($z = 2.16$, $p < .05$). Other than chance, we presently cannot offer an explanation of this anomaly.

processing units and, perhaps, their speed of execution are the basis for intelligence remains an attractive idea, but the search for those units and their crucial properties undoubtedly will be a formidable task. On the basis of our analysis, we recommend that such investigations avoid any possible visual angle effects by presenting all stimuli at a fixed focal point. Only by carefully eliminating the sources of data contamination can investigators hope to identify consequential processing units, should they, in fact, exist.

The second implication concerns a possible new line of inquiry. The findings from the three new experiments suggest that individual differences in the ability to scan the visual field may be a fruitful topic to pursue in its own right, in terms of its relation to intelligence. Some of the obvious questions emerging from such a line of inquiry include issues that have already been raised in regard to intelligence. For instance, are faster subjects employing different scanning strategies? Does an attentional factor play a role? Both of these factors already have been proposed by researchers in the area as important constituents of intelligence (Carlson & Widaman, 1987; Marr & Sternberg, 1987), and further investigation of individual differences regarding the scanning of visual fields and IQ may help in providing the answers to these and other related questions.

Finally, it is possible, after all, that Galton was not wrong in attempting to analyze intelligence in terms of fundamental perceptual-motor elements. But the greatest hurdle in pursuing such an approach is to ensure that the elements are sufficiently isolated in our experiments as to be uniquely identified. In this article, we have shown that existing research interpreted as providing evidence for a mental speed contribution to intelligence in a prevalent paradigm has not met this criterion of unique identifiability. In so doing, we have identified another variable—visual angle—that appears worthy of further exploration.

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