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Jensen's Use of the Hick Paradigm: Visual Attention and Order Effects

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Longstreth (1984, 1986) and Carroll (1987) have recently raised questions concerning the effects of practice and order and retinal displacement in Jensen's use of the Hick paradigm. The results of this study indicate that the effect of practice and order is nonsignificant. The effect of retinal displacement, although significant, accounts for such a small amount of the variance as to be of little practical or theoretical importance in Jensen's investigations with the Hick paradigm.

Jensen's investigations of choice reaction-time (RT), as measured in the Hick paradigm, in relation to intelligence (IQ), or psychometric *g* (e.g., Jensen, 1982, 1985; Jensen & Munro, 1979; Jensen, Schafer, & Crinella, 1981; Vernon & Jensen, 1984), have recently been questioned by Longstreth (1984, 1986) and Carroll (1987). Although Jensen has also used a variety of other chronometric procedures besides the Hick paradigm in his study of *g*, Longstreth's and Carroll's critiques are focused solely on Jensen's use of the Hick paradigm, named after Hick's law (1952), which states that RT increases linearly as a function of the logarithm of the number of choice alternatives (*n*), usually scaled in bits (i.e., $\log_2 n$, or the amount of information needed to reduce stimulus uncertainty by half). The critiques question certain points in Jensen's procedure, data analysis, and theory relating the Hick paradigm to intelligence.

The response by Jensen and Vernon (1986) effectively answers most of Longstreth's criticisms. Also a recent meta-analysis (Jensen, 1987) of studies of the Hick paradigm contradicts several of Longstreth's conjectures regarding the RT–IQ relationship. This meta-analysis of the results of numerous studies by Jensen and others indicates that individual differences in RT, as well as the slope of the regression of RT on stimulus set-size scaled in bits are, in fact, significantly correlated (negatively) with IQ, and that the RT–IQ correlation increases linearly as a negative function of stimulus set-size scaled in bits.

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Longstreth (1984) also discussed the potentially equivocal impact of several procedural variables in Jensen's studies, namely, practice and order effects, visual attention effects, and response bias. The response (Jensen & Vernon, 1986) to these particular criticisms, however, was not buttressed by directly relevant empirical data. Data that directly address these points were not available in the studies that entered into the aforementioned meta-analysis. Hence, specific new experiments are needed to answer these questions. Discussion is here focused on the effects of *practice*, of *order*, and of *visual attention*.

PRACTICE AND ORDER EFFECTS

In Jensen's choice RT investigations with the Hick paradigm, stimulus set-size has always been presented in the ascending order of 0, 1, 2, and 3 bits, usually with 15 trials at each level. In the standard order of presentation subjects thus have the least amount of practice in the 0 bit condition and the most with 3 bits. Therefore, as Welford (1986) has noted, the effect of practice across trials is confounded with increasing stimulus complexity, which could result in an underestimation of RT slope. Moreover, this negative bias is likely to be more pronounced the higher an individual's IQ, as fast learners would be more likely to evince greater transfer from the 0 bit to the 3 bit condition than slow learners.

Jensen and Vernon (1986) countered Longstreth's (1984) conjectures concerning the effects of practice and order only indirectly and inferentially, by presenting data comparing (1) the means of subjects' median RTs on the first and last 3 of 15 trials, for both intercept and slope of RT on set-size, (2) the regression of RT on bits of the first and last 15 of 30 trials, and (3) the regression slope and intercept across test sessions on successive days. Jensen and Vernon concluded from their analysis that practice effects produced "no evidence of significant departure from linearity, or Hick's law, in the overall mean RT data obtained with Jensen's apparatus and procedure" (p. 167).

But this conclusion, even though correct, does not directly confront Longstreth's query. The data referred to by Jensen and Vernon can only reflect the effects of practice *within* each set-size. Although it may *seem* improbable that practice effects would be manifested *between* set-sizes when the data fail to show significant effects *within* set-sizes, actually no definitive statement can be made regarding this issue without experimentally varying the order of set-size presentation.

Such experiments have recently been reported by Larson and Saccuzzo (1986) and by Widaman and Carlson (in press). Larson and Saccuzzo failed to find evidence of a systematic difference between the standard order (0, 1.58, and 2.32 bits) and random order (all possible order permutations) of set-size presentation on any of the Hick RT parameters. Their results, however, seem inconclusive with respect to Jensen's studies. Curiously, after criticizing Longstreth's (1984) "mini-experiments" for substantially changing stimuli spatial position in comparison to Jensen's apparatus, Larson and Saccuzzo (1986) used a markedly different apparatus themselves (a "TRS-80 version"). Their apparatus, for example, had a horizontal stimulus array instead of an arc of lights; there was no auditory preparatory stimulus; and it used a commercial computer keyboard space bar instead of a "home button," which Jensen (1985) considers inadvisable. More importantly, although Larson and Saccuzzo included appropriate correlations between median RT and bits and the regression of RT on bits for each presentation order, they reported no tests of statistical significance. In any case, the small number of subjects (ranging from 1 to 5) within the random conditions probably would be unlikely to provide enough statistical power to reject the null hypothesis.

Widaman and Carlson (in press), on the other hand, used an apparatus that is virtually identical to Jensen's, and they conducted the appropriate statistical tests of significance with a sufficient sample size (N = 74). In their study, set-sizes were administered in the following orders: (1) standard order (1, 2, 4, and 8 light/buttons); (2) reversed order (8, 4, 2, and 1 light/buttons); and (3) random order. In each case, there was an equal number of trials within each set-size. In contrast to the results obtained by Larson and Saccuzzo, Widaman and Carlson found small but fully significant practice effects on all the Hick RT parameters. Specifically, they demonstrated that, relative to the random order of presentation, administration of set-sizes in the standard order resulted in an *underestimation* of RT slope and an *overestimation* of the intercept, while administration of set-sizes in the reversed order resulted in an *overestimation* of RT slope and an *underestimation* of the intercept. Widaman and Carlson attributed these results to different cumulative amounts of practice at each respective set-size. Hence, they also recommend administering the various set-sizes in random order as a means of obviating such cumulative practice effects in future research with the Hick paradigm.

The present investigation takes a further look at the effects of practice and order, using the identical apparatus that was used in all of Jensen's previous studies of the Hick paradigm.

VISUAL ATTENTION EFFECTS

The question of extraneous visual attention effects was also raised by Longstreth (1984):

> Jensen's apparatus permits visual scanning to a magnitude shown in other experiments to affect RT as well as identification accuracy. Facing the Jensen apparatus with a finger resting on the home button as befitting the typical subject, the subject's eyes would be perhaps a foot and a half away from that button. If the eyes addressed one of the extreme lamps, the other extreme lamp would be displaced about 30 deg. from the point of foveal attention. If the attention point is the home button itself, all lamps are displaced about 12 to 15 deg. Now, studies of retinal displacement show detrimental effects at much *smaller* distances. (p. 146)

If Longstreth's (1984) conjecture is correct, it would be impossible, with Jensen's apparatus alone, to separate the effects of individual differences in information processing rate and the effects of retinal displacement.

This question was also recently tested by Widaman and Carlson (in press), using an apparatus very similar to Jensen's. In their experiment, the positions of the lights within each set-size were systematically varied. The results failed to support the contention that this spatial aspect of visual attention span affects any of the Hick parameters. As Widaman and Carlson correctly note, however, the effects of retinal displacement and response bias in their investigation are confounded, because varying light placement within bit conditions also requires different ballistic responses. Nevertheless, even though these extraneous procedural variables should impact RT parameters synergistically, their effects did not even approach statistical significance.

In addition to investigating the effects of practice and order on RT parameters with the Hick paradigm, the present study examines the effect of retinal displacement on RT, using both Jensen's original apparatus and a Gerbrands RT apparatus capable of eliminating this confounding interaction by presenting the 1 bit set-size (a red and a green light) at one and the same aperture on the response console.

METHOD

Subjects

Two separate experiments are reported, each based on independent samples of 40 subjects, nearly all of them students at the University of California at Berkeley. The subjects were recruited as paid volunteers through an advertisement in the campus newspaper.

Chronometric Apparatus

The original Jensen apparatus was used in both experiments. This apparatus (first described in Jensen & Munro, 1979) consists of a 13 in. by 17 in. console tilted at a 30-degree angle. The "home button," a red pushbutton ½ in. in diameter, arranged equidistantly from the home button in a semicircle with a 6-in. radius. One half inch above each response button is a faceted green light ½ in. in diameter. Plastic flat black overlays can be fastened to the console exposing different light/button combinations. Normally exposed are the set-sizes of 1, 2, 4, and 8 lights/buttons (corresponding to 0, 1, 2, and 3 bits). If these light/button pairs are numbered 1 through 8 from left to right, the following combinations are exposed:

Set Size (n)	Light/Button Position
1	5
2	4, 5
4	3, 4, 5, 6
8	All positions

In Jensen's procedure, a single trial consists of: (1) the subject depresses the home button; (2) an auditory warning signal (a "beep" of 1-s duration) is presented; (3) following a random interval of 1 to 4 s, one of the lights goes on; (4) the subject, as quickly as he or she can, removes his or her finger from the home button and depresses the pushbutton directly below that light. The apparatus allows the separate measurement of RT and movement time (MT). RT is the amount of time it takes the subject to lift the finger off the home button after presentation of one of the lights. MT is the interval between releasing the home button and depressing the pushbutton directly below the illuminated light. RT and MT are recorded in milliseconds (ms) by two electronic timers.

A second apparatus, a Gerbrands reaction timer, was used only in the experiment on visual attention. This apparatus, henceforth referred to as the "color box," consists of a 5 in. by 6½ in. console, 2½ in. in height. In the center of the apparatus, flush with its surface, is a circular aperture, approximately 1 in. in diameter, in which different colored lights (viz., red, green, or yellow) can be illuminated. Directly 1 in. above this light, protruding upward ¼ in. from the surface of the apparatus, is a round yellow light, ¼ in. in diameter, which acts as the preparatory stimulus. Instead of response buttons, there are two Morse keys (one red and one green), 1 in. in diameter, side-by-side in the middle of the front of the apparatus.

The procedure for the color box is the same as that for the Jensen apparatus: (1) the subject depresses one or both of the Morse keys, depending on set-size (one key is depressed with the forefinger of the preferred hand for the 0 bit condition, whereas both keys are held down with the forefingers of both hands for the 1 bit condition); (2) a *visual* warning signal (a small yellow light of 1-s duration) appears; (3) following a random interval of 1 to 4 s, one of the two colored lights is presented (only the red light in the 0 bit condition and either the red or the green light in the 1 bit condition); (4) the subject, as quickly as he or she can, lifts his or her finger off the Morse key corresponding to the color of the stimulus light. (When the subject erred in the 1 bit condition by lifting two fingers instead of one, the trial was re-run after administration of all the other trials, just as was done for erroneous trials on the Jensen apparatus.) The color box records only RT, which is the time it takes the subject to lift the finger off the Morse key after presentation of the stimulus. RT is recorded (in ms) by an electronic timer.

Procedure

Experiment I: Practice and Order Effects. Subjects ($N = 40$) were randomly assigned to either the *standard* condition or the *reversed* condition. The *standard* group was administered the set-sizes in the usual ascending order (0, 1, 2, and 3 bits). The *reversed* group was administered the set-sizes in the reversed order (3, 2, 1, and 0 bits). The light/button combinations used for both groups at each set-size were the identical ones exposed by the overlays mentioned above. Both groups received 30 trials at each set-size, for a total of 120 trials.

Although the number of trials per bit condition used in 34 previous studies of the Hick paradigm has varied from 11 to 64, most of the studies (22 to be exact) have used 15 trials, while only 10 studies have used more than 15 trials (Jensen, 1987, Table 2, pp. 112–114). In deciding to use 30 trials for the present study, we considered what seemed the relative advantage of increasing the reliability of measurement by using more trials than the 15 used in most studies, even though recognizing that if the results were based on 15 trials they would be more comparable to a larger number of previous studies. However, analyses of previous studies (Jensen, 1987, pp. 126–133) have generally shown such utterly nonsignificant effects of practice (over trials within bit conditions) that it seemed desirable to increase the reliability and precision of the data for the present study, thereby increasing the chances of detecting significant practice effects, by administering more trials than in most previous studies. We were also concerned with the possibility that, with fewer trials, it could be argued that the evidently slight practice effects did not have a sufficient number of trials to show up significantly. And we knew of no basis for expecting that, if a practice effect should occur mostly in the first half of the total number of trials, its statistical detection would be counteracted by the additional trials. All things considered, therefore, the use of 30 trials, rather than 15, seemed methodologically preferable to us.

Experiment II: Visual Attention Effects. Subjects ($N = 40$) were randomly assigned to either the *spread* condition or the *adjacent* condition. Both groups, regardless of condition, were initially administered the 0 bit task in the normal position (light/button 5) on the Jensen apparatus. Following this, subjects in the *spread* condition were administered the 1 bit task with the lights/buttons in positions 1 and 8, thereby allowing *maximal retinal displacement*. Subjects in the *adjacent* condition were administered the 1 bit task in the usual adjacent light/button positions (i.e., lights/buttons 4 and 5), which affords the *minimal retinal displacement* possible on this apparatus.

In a counter-balanced design, the subjects in each group were then given the 1 bit task with the light/button positions opposite to the ones they had initially received; that is, the subjects in the *spread* group, who were first administered the 1 bit task in the light/button positions 1 and 8, received the 1 bit task with the light/button positions 4 and 5, whereas subjects in the *adjacent* condition, who initially received the 1 bit task in light/button positions 4 and 5, were administered the 1 bit task in light/button positions 1 and 8. Subjects were given 30 trials in each of the three conditions.

After they were tested on the Jensen apparatus, all subjects, in both groups, were administered the 0 bit and 1 bit tasks on the Gerbrands "color box" reaction timer. The 0 bit task, administered first, consisted of the presentation of the red light only. The 1 bit condition consisted of the presentation of either the red light or the green light. Subjects were given 30 trials at each bit condition.

RESULTS

The results of each experiment are described separately, as the statistical analyses that were conducted varied according to the experiment. The statistical analyses in each experiment were performed both with and without outliers (data more than two standard deviations away from the mean). The results from these two sets of analyses, however, were substantively identical. Therefore, the results directly answering the main question of each experiment (i.e., the effects of practice and order and visual attention) are based on all the raw data ($N = 40$).

Experiment I: Practice and Order Effects

Table 1 presents the mean median RTs and MTs for the set-sizes of 0, 1, 2, and 3 bits, as well as slopes and intercepts for each presentation order. Figure 1 displays these results graphically. In the last column in Table 1, the degree of fit to the linear regression of RT on bits, or the conformity to Hick's law, is indicated by the size of the Pearson *r*. All of these mean medians, slopes, intercepts, and degrees of fit, for both presentation orders, are consistent with

TABLE 1
Mean Median Reaction Time (RT) and Movement Time (MT) as a Function of Bits, and Regression of RT and MT on Bits

	Bits				Regression		
Group[a]	0	1	2	3	Int.	Slope	r^b
Standard							
RT	289	325	347	362	295	24	.981
MT	201	191	202	205	196	2	.489
Reversed							
RT	298	339	361	375	306	25	.972
MT	211	214	226	241	208	10	.966

[a]In each group $N = 20$.
[b]Pearson r_{xy} based on $N = 4$, i.e., x = number of bits (0, 1, 2, 3), y = mean median RT (or MT) at each level of bits.

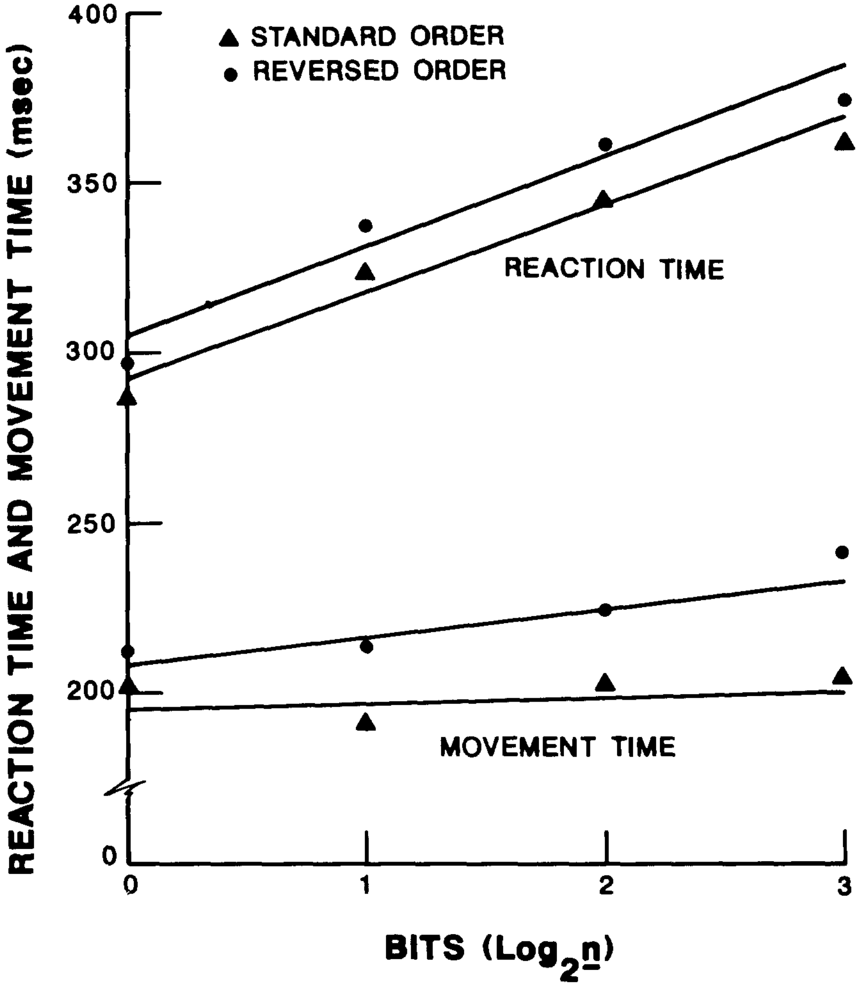

FIG. 1. Regression of reaction time (RT) and movement time (MT) on bits.

those obtained from similar samples of university students, with the exception of the correlation between the number of bits and the mean median MT at each level of bits for the reversed condition (see Jensen, 1987).

Table 2 shows results of a series of *t* tests conducted on all the relevant RT and MT parameters (Welch-Aspin *t* tests based on unequal variances were conducted when necessary). The only significant *t* test at the .05 level is for the slope of MT ($t = 2.01$, $df = 37.32$, $p = .05$). Moreover, all of the *t* tests for the RT parameters are nonsignificant (all *t*s < 1.00). It is interesting to note that greater variability was observed for the reversed order of presentation for both RT and MT intercepts.

TABLE 2
Independent Groups *t* Tests for Reaction Time and Movement Time Slope and Intercept

Dependent Variable	Set-Size Presentation Order[a] Standard *M*	Standard *SD*	Reversed *M*	Reversed *SD*	*t* Test *t*	*p*	df
Reaction Time							
Slope	23.91	12.07	25.15	9.62	0.36	.72	38
Intercept	295.03	31.71	305.61	47.32	0.83	.41	33[b]
Movement Time							
Slope	2.18	11.87	10.27	13.60	2.01	.05	38
Intercept	196.46	38.41	207.91	64.41	0.68	.50	31[b]

[a]In each presentation order $N = 20$.
[b]Welch–Aspin *t* test based on separate variances.

To further examine the effects of practice and order on RT and MT, an additional set of *t* tests was conducted for the mean median RTs and MTs across each set-size. Again, all *t* tests for RT at each set-size are nonsignificant (all *t*s < 1.00). The only *t* test for the MTs approaching statistical significance is at the 3 bit condition ($t = 1.83$, $df = 38$, $p < .08$). In sum, the results of this analysis indicate that the only significant effect of practice and order is for the 3 bit condition with the least amount of practice. The effects of practice and order on RT and MT on the original Jensen apparatus thus appear to be negligible.

Experiment II: Visual Attention Effects

As a preliminary analysis, *t* tests were conducted on the counterbalanced groups for the mean medians of the 0 and 1 bit conditions. As none of the *t* tests was significant at the .05 level, the data of the counterbalanced groups were pooled for all further analyses. The results of the pooled data are displayed graphically in Figure 2. The marked differences between the 0 bit and 1 bit mean medians for RT on the Jensen apparatus and the color box clearly demonstrate the impact that disparate apparatuses can have on simple and choice reaction time. The average difference of 137 ms between the RTs at the 0 and 1 bit conditions on the color box is fully significant (correlated $t = 19.84$, $df = 39$, $p < .001$). We can offer no explanation why simple RT (0 bit) on the color box is so much faster than on the Jensen apparatus, but the fact that the difference in RT between 0 and 1 bit is much greater on the color box is most likely due to the condition that choice RT (1 bit) on the color box requires the subject to lift the forefinger of either the left or the right hand, depending on the color of the reaction stimulus, which always appears in one and the same location for both colors. Choice RT on the Jensen apparatus, however, requires lifting only one and the same finger from the single home button on every trial, while the choice stimuli are presented at two different locations.

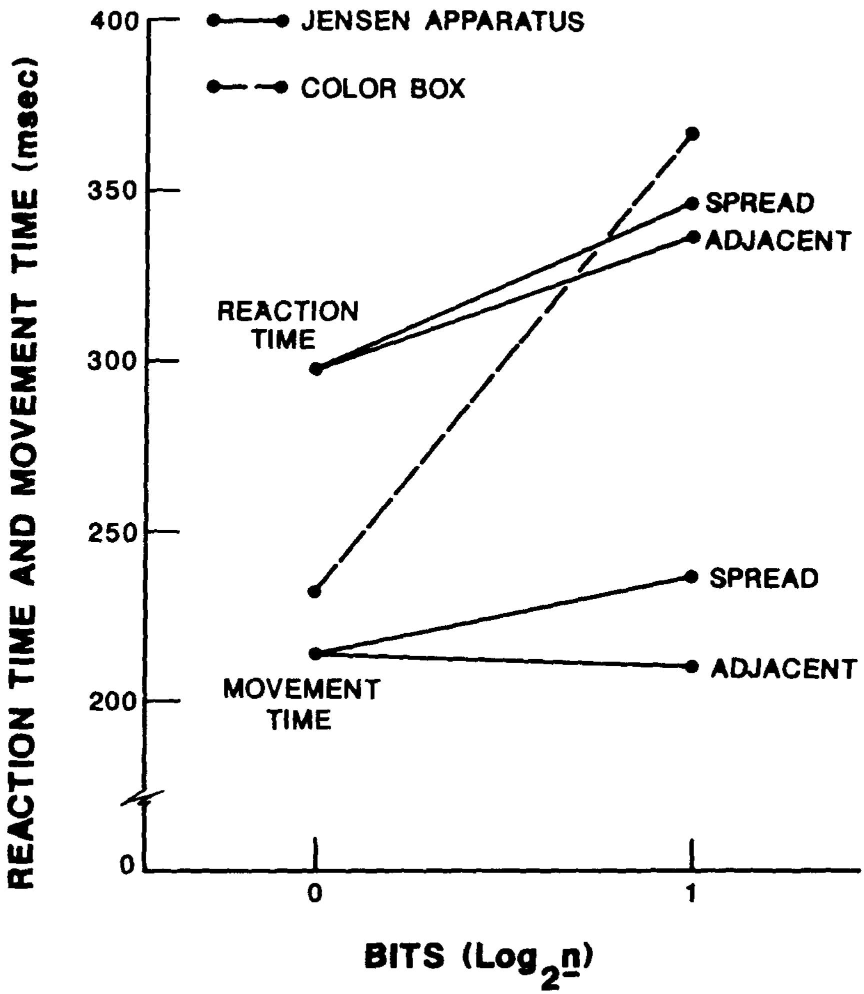

FIG. 2. Mean median reaction time (RT) and movement time (MT) across bits.

A repeated-measures analysis of variance (ANOVA) was performed for both RT and MT on the Jensen apparatus, with the 1 bit spread and adjacent condition as the within-subjects effect. Shown in Table 3, the results of these analyses indicate significant Conditions (within-subjects) effects for both RT ($F\,(1, 39) = 6.07, p < .05$) and MT ($F\,(1, 39) = 6.14, p < .05$). Both RT and MT are higher in the spread condition than in the adjacent condition. The last column in each source table displays eta-squared (η^2) for each effect. In spite of the fact that the Conditions (within-subjects) effects are statistically significant, the actual amount of variance explained by Conditions for RT ($\eta^2 = .01$) and MT (η^2

TABLE 3
Repeated-Measures Analysis of Variance for Reaction Time and Movement Time

		Reaction Time			Movement Time		
Source	df	ms	F	η^2	ms	F	η^2
Subjects	39	7238.64	27.14**	.96	9591.58	8.32**	.88
Conditions	1	1620.00	6.07*	.01	7078.20	6.14*	.02
Residual	39	266.74			1152.40		

$*p < .05$; $**p < .001$.

= .02) is negligible. In contrast, individual differences (between-subjects) account for 96% of the variance on RT and 88% of the variance on MT. The minor impact of visual attention effects on individual differences in RT and MT is further reflected in the very large correlations between the 1 bit spread and adjacent conditions for both RT (r = .91) and MT (r = .93). In brief, visual attention effects on RT and MT are statistically significant, but quite small in relation to individual differences.

A surprising and presently inexplicable feature of Figure 2 is the significant increase in MT between 0 and 1 bit in the spread condition. Significant variation in mean MT is quite untypical for data in the Hick paradigm. The vast majority of previous studies have shown no significant mean differences in MT as a function of bits, and the differences between 0 and 1 bit are invariably nonsignificant and of much lesser absolute magnitude than is seen in the present data (see Jensen, 1987, pp. 122–124). Even the difference in MT between 0 and 3 bits (i.e., the 8 light/button condition) in previous studies is not as great as the MT difference between 0 and 1 bit for the spread condition of the present study, shown in Figure 2. Why this occurred is a mystery.

DISCUSSION

The intent of this study was to answer questions raised in recent critiques by Longstreth (1984, 1986) and Carroll (1987) regarding the effects of practice and order and retinal displacement in Jensen's use of the Hick paradigm.

Regarding the effects of practice and order on the Hick paradigm, the results of the present study do not support Longstreth's (1984) conjectures. Indeed, systematic variation of the standard and reversed presentation orders in this study, using the original Jensen apparatus, provides no evidence of a positive bias in estimation of the RT intercepts or a negative bias in estimation of the RT slopes. If such biases were manifested, the RT regression lines for the standard and reversed orders would not be parallel. However, the regression lines are in fact almost perfectly parallel, with slopes of 24 and 25 ms/bit. In addition, the degree of conformity to Hick's law for both the standard and reversed orders of presentation is wholly consistent with previously obtained results using the standard order of presentation with university samples (see Jensen, 1987). The only statistically significant effect of practice and order found in this study was for the slope of MT. This significant difference, however, is entirely attributable to a significantly higher score on the 3 bit condition in the reversed presentation order. In other words, MTs were only higher in the reversed order of presentation with maximal stimulus complexity and minimal amounts of practice. As this significant difference between groups appeared only on the 3 bit condition (there are no significant differences between presentation orders at any other set-size for both RT and MT), it is plausible that more practice trials would have eliminated what little differences were observed in MT. In sum, the results of this study indicate that the effects of practice and order are not confounded with increasing stimulus complexity as a result of presentation order. It is troubling, of course, that the only other study (Widaman & Carlson, in press) of the effect of order of presentation of the bit conditions on the intercept and slope of RT in the Hick paradigm that used an apparatus almost identical to Jensen's showed significant differences in intercept and slope between the standard and reversed orders. (The reversed order lowered the intercept and increased the slope, while the standard order did the opposite, both relative to the randomized order). We find no fault with the Widaman and Carlson experiment that would cause us to question its results. The main procedural difference from the present study was that 15 trials, instead of 30, were administered at each bit condition, but we can think of no clear rationale by which this factor could account for the noted difference in results between the two experiments. Any attempt to explain the discrepancy, based on the available information, would amount to mere speculation. The fact that practice effects have been demonstrated in certain other RT paradigms (Teichner & Krebs, 1974) and under quite different conditions, usually with many more trials than were used in either of the studies under discussion, affords no basis for resolving the disagreement in results. In the face of an empirical contradiction, we can only conclude that the particular issue, unfortunately, remains unresolved and in need of more investigation.

With regard to the effects of retinal displacement on the RT and MT parameters, Longstreth's (1984) conjectures appear to have been partially substantiated. Significant effects were noted for both RT and MT. In each case, RTs and MTs were higher for the set-size with maximal retinal displacement. This also contradicts the findings of Widaman and Carlson (in press). However, in spite of the statistical significance of these findings, the variance accounted for by this effect is small. Individual differences in RT and MT (plus measurement error) account for 95% and 88% of the variance, whereas the effects of retinal displacement account for only 1% and 2%, respectively.

Finally, the results obtained with the color box and the comparison of results of the present study to those of Widaman and Carlson (in press) clearly demonstrate that, although the relationship between RT and stimulus complexity holds across apparatuses, evidence of extraneous factors on one apparatus does not necessarily imply that they are evident on all apparatuses, as was demonstrated with this study. It appears that different RT apparatuses make subtly different sensorimotor and processing demands.

The results of the present study lend no support to the gist of Longstreth's contentions. The effects of practice and order on the parameters of the Hick paradigm appear negligible, and the effect of retinal displacement, although significant, is so small, relative to individual differences in RT and MT, as to be of no practical or theoretical importance in the context of Jensen's research with the Hick paradigm. Also, the results obtained from the color box indicate that the use of a different RT apparatus may yield rather different parameter values. Hence, the main parameters of Jensen's investigations of individual differences in reaction time with the Hick paradigm do not appear to be appreciably affected by the particular experimental variables that Longstreth conjectured might have important effects.

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