JOURNAL OF EXPERIMENTAL CHILD PSYCHOLOGY 40, 181–192 (1985)

Development of Mental Rotation: A Speed–Accuracy Study

ROBERT KAIL

Purdue University

Pairs of letters and numbers were shown to 11-, 14-, and 19-year-olds. One stimulus in a pair was presented upright. The second, which was either identical to the first or a mirror image of it, was rotated 0 to 150° from the vertical. Individuals judged if the stimuli in a pair would be identical or mirror images if presented at the same orientation. They did so under instructions that emphasized accurate responses, fast responses, or fast and accurate responses. Typically, responses were (1) most accurate and slowest when accuracy was emphasized, and (2) least accurate but fastest when speed was emphasized. The data from the three instructional conditions were used to derive measures of response times in which accuracy of response was equated for the three age groups. At 95% accuracy 14- and 19-year-olds mentally rotated stimuli at the same rate, which was faster than 11-year-olds' rate. At 100% accuracy, 19-year-olds mentally rotated stimuli more rapidly than both 11- and 14-year-olds, who did not differ from one another.

Reaction time paradigms have had a growing role in cognitive developmental psychology in the past several years. By arranging experimental conditions appropriately, total response time can be used to determine the organization of cognitive processes and to estimate their durations. Procedures of this sort have been used successfully to study development in several cognitive domains, including retrieval from memory (e.g., Bisanz, Danner, & Resnick, 1979; Gitomer, Pellegrino, & Bisanz, 1983), analogical reasoning (e.g., Sternberg & Nigro, 1980; Sternberg & Rifkin, 1979), mental arithmetic (Ashcraft, 1982), and spatial aptitude (e.g., Carter, Pazak, & Kail, 1983).

In most of this research, subjects are encouraged to respond accurately and to do so as rapidly as possible. Typically, subjects are not explicitly

I am grateful to Barbara Irzyk for her help in testing subjects and in analyzing data, to Charles Nelson, James Pellegrino, and Tim Salthouse for their comments on a previous draft of this manuscript, and to staff members and students at the following schools for their friendly cooperation throughout this experiment: Attica Elementary School, Attica Junior–Senior High School, Bon Air School, Edgelea Elementary School, Sunnyside Junior High School, and Tecumseh Junior High School. Requests for reprints should be sent to Robert Kail, Department of Psychological Sciences, Purdue University, West Lafayette, IN 47907.

0022-0965/85 $3.00

instructed as to an appropriate speed of response or level of accuracy. Hence, they must set their own criterion for a speed of response that will lead to acceptably high levels of accuracy. For adults, there is a trade-off between the speed and accuracy with which an individual responds (Pachella, 1974). Encouraged to respond faster, individuals will usually err more often; asked to respond more slowly, they will err less frequently.

This "speed–accuracy trade-off" presents a serious interpretive problem in developmental research. Suppose that for both children and adults slower responses are associated with higher levels of accuracy, a situation depicted in Fig. 1. Small developmental differences in accuracy can lead to apparent similarities in processing rate. For example, children might be accurate on 90% of the trials and adults on 95%, a difference many investigators would simply dismiss. Yet, as illustrated in Fig. 1, the conclusion of similarity in processing rate is a by-product of these small differences in accuracy. The appropriate comparison for Point A in Fig. 1 is Point C, for these points are matched in accuracy. In like manner, the appropriate comparison for B is D.

In fact, Fig. 1 probably represents the least complex situation: The speed–accuracy trade-off function is linear and the functions are parallel, implying that children and adults trade off speed and accuracy at the same rate. If either of these simplifying assumptions were inaccurate, then it would be even more complicated to compare processing times for different age groups.

The situation in Fig. 1 is not simply hypothetical. Bisanz et al. (1979), for example, used a variant of the Posner (1969) matching paradigm in which subjects decided if pairs of stimuli were identical physically (i.e., physical match) or in name (i.e., name match). Name matches took more

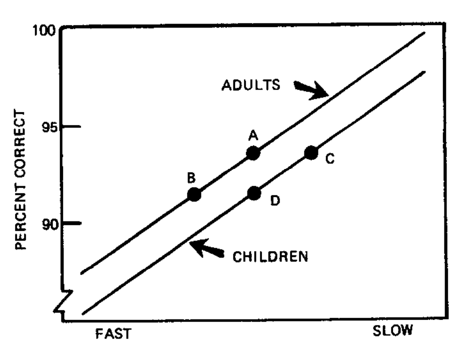

FIG. 1. Hypothetical functions illustrating changes in accuracy associated with changes in response time, separately for children and adults. A common outcome in developmental research is represented by Points A and D, in which response time is similar for children (or adolescents) and adults but accuracy is not.

time than did physical matches, presumably reflecting the additional time needed to retrieve the names of the stimuli from semantic memory. These values did not differ significantly for 12- and 19-year-olds (97 and 80 ms, respectively), suggesting that name retrieval reaches adultlike speeds in late childhood. However, differences in accuracy preclude reaching this conclusion with confidence: 12-year-olds were less accurate (94.9%, the average of 95.8% accuracy on physical matches and 94% on name matches) than 19-year-olds (97.85%, the average of 98.7 and 97.7%). In other words, the Bisanz et al. data may correspond to the situation represented by Points A and D in Fig. 1.

Similarly, speed–accuracy trade-offs may help to explain discrepant findings in previous developmental studies on mental rotation. In this research, subjects are shown two versions of a stimulus that vary in orientation: One is upright and the other, the comparison stimulus, is rotated 0–180° from the vertical. Subjects decide if the two versions of a stimulus are identical or mirror images. The time to do so increases linearly as a function of the orientation of the comparison stimulus, reflecting mental rotation of the comparison stimulus to the vertical (Cooper & Shepard, 1973).

Some investigators (e.g., Kail, Pellegrino, & Carter, 1980) have reported age-related changes in the speed with which subjects mentally rotate stimuli to the vertical, but others have reported age invariance in rotation rate (Childs & Polich, 1979; Waber, Carlson, & Mann, 1982). Notably, age differences in error rates are largest in studies reporting age invariance in mental rotation (Childs & Polich, 1979; Waber et al., 1982) but negligible in the Kail et al. (1980) study reporting age differences in rotation rate. Subjects in these various studies may have adopted different speed and accuracy criteria, making it difficult to compare the results across these studies.

One approach to the problem of speed–accuracy trade-offs is to require subjects to perform a task under instructions that stress either accuracy or speed. These data can then be used to make age comparisons in processing speed with accuracy held constant. In the present study, 11-, 14-, and 19-year-olds were tested on a mental rotation task under instructions that emphasized responding accurately, responding rapidly, or responding both accurately and rapidly. Testing subjects in this manner yielded evidence pertinent to three questions: (1) Is there a speed–accuracy trade-off in performance on the mental rotation task? That is, when subjects increase response speed, do error rates increase, and, conversely, when people slow their responses, are errors less frequent? (2) Is the speed–accuracy trade-off comparable for individuals of different ages? (3) Are there age differences in rate of mental rotation when accuracy is comparable for individuals of different ages?

METHOD

Participants

Forty-eight individuals (24 males, 24 females) were tested at each of three grade levels: Grades 4 and 5 (median age 11-0), Grades 8 and 9 (14-4), and college (19-5). At each age level, 8 males and 8 females were assigned to each of three instructional conditions (speed emphasis, accuracy emphasis, neutral instructions). Subjects in Grades 4, 5, 8, and 9 attended public schools in small communities in the midwestern United States; adults were undergraduates who participated to satisfy a course requirement.

Stimuli

Slides of alphanumeric characters from the Kail et al. (1980) study were used. Six slides were prepared for each of the following alphanumeric characters: 4, 5, F, G, J, L, P, R. Each slide consisted of one of the characters presented upright; adjacent to it was the same character or its mirror image, rotated 0, 30, 60, 90, 120, or 150° clockwise from the vertical. Each alphanumeric was presented twice in three of the six orientations, once as an identical pair and once as a mirror-image pair.

The 48 slides were ordered randomly, subject to the following constraints: (1) each combination of orientation and response (identical, mirror images) appeared once in every block of 12 trials; (2) each alphanumeric character appeared once in every block of 8 trials; (3) no character or orientation appeared on successive trials; and (4) no response appeared more than three times in succession.

Apparatus

Slides were projected onto a screen approximately 1 m from the subject. Presentation of a slide started a timing loop (via a fiber-optic cable) in a Cromemco Z-2 computer. Subjects responded by pressing, with the index finger of their preferred hand, one of two identical 2.5-cm diameter buttons mounted on top of a response box, thereby stopping the timing loop. Response time and accuracy were recorded by the computer, which initiated the next trial after an interval of approximately 2 s.

Procedure

Subjects were told to decide if the stimuli in a pair were identical or mirror images. Twelve practice trials were given in which slides were shown and the experimenter rotated letters printed on a 3 × 5 card to show how characters could be rotated to judge if pairs were identical or mirror images. During these trials, subjects were given feedback by the experimenter as to the accuracy of their responses. The 48 slides were then shown. On a correct response, the computer terminal emitted a readily audible, high-pitched tone.

After these trials, subjects received different instructions depending upon their group. Subjects in the *control condition* were simply told that they had done well and should continue to solve the problems in the same way. Subjects in the *speed-emphasis condition* were told that "you made *n* mistakes. Most people your age make many more mistakes than you did. So, this time when I show you the slides, I think you can try to answer a little faster than you did last time, even though you might make a few more mistakes." Subjects in the *accuracy-emphasis condition* were told that "you made *n* mistakes. This time when I show you the slides, it would be a good idea if you answered more slowly. That way you'll get more of them correct." For these latter two groups, the number of errors (*n*) was recorded by the computer and displayed on the computer terminal for the experimenter directly after the final trial.

These instructions were followed by presentation of the 48 slides two more times. Between the two presentations, subjects received instructions appropriate for their group. For subjects in the control condition, the instructions used after the first presentation of the slides were repeated. Subjects in the speed-emphasis condition were told: "Answering faster worked well for you that time, so keep doing it. Answer faster, even if you make a few more mistakes." Subjects in the accuracy-emphasis condition were told: "'Answering more slowly worked well for you that time, so keep doing it. Answer more slowly and you won't make as many mistakes." Testing required approximately 20 min.

RESULTS

The first set of analyses concerns the effectiveness of the instructions in changing the speed and accuracy of subjects' responses. The second set concerns developmental comparisons in latency measures among groups matched in accuracy.

Impact of Instructions on Speed and Accuracy

Accuracy. The mean number of correct responses is shown as a function of orientation in Fig. 2. These data were analyzed with a 3 (age) × 3 (condition) × 2 (sex) × 6 (orientation) × 2 (response) analysis of variance. There were significant effects for age, $F(2, 126) = 3.3, p < .05$, condition, $F(2, 126) = 22.15, p < .01$, and orientation, $F(5, 630) = 55.48, p < .01$, but each of these effects was qualified by significant interactions. Three interactions—involving age, response, and orientation—replicate previous findings of Carter et al. (1983). First, the interaction of age and orientation, $F(10, 630) = 1.96, p < .05$, reflected the fact that accuracy decreased more rapidly as a function of orientation for children and adolescents than for adults. Second, the interaction of response and orientation, $F(5, 630) = 14.58, p < .01$, was due to the fact that accuracy decreased more rapidly as a function of orientation on identical pairs than on mirror-image pairs. Third, each of these interactions must be interpreted in light of the significant interaction among age, response, and orientation, $F(10, 630) = 1.89$, $p < .05$: The interaction between response and orientation was particularly evident for children and diminished with age.

Central to the present study are three interactions that reflect the influence of the instructions given to subjects concerning speed or accuracy of response. The interaction of condition and orientation was significant, $F(10, 630) = 5.86$, $p < .01$. Accuracy decreased as a function of orientation in all conditions, F's$(5, 630) \geq 4.33$, $p < .01$, but the decrease was greatest when instructions emphasized speed. The interaction of age with condition and orientation was also significant, $F(20, 630) = 1.78$, $p < .05$. The locus of this interaction can be seen in Fig. 2. The impact of instructions increased with increases in orientation, particularly for adolescents and adults. For example, the simple interaction of condition and age was significant at 150°, $F(4, 630) = 8.76$, $p < .01$, but not at 0°. At 150°, the difference in performance between instructions that emphasized accuracy versus those that emphasized speed was 6, 20, and 19% for 11-, 14-, and 19-year-olds, respectively. Corresponding values at 0° were 2, 4, and 6%.

Two other interactions involving conditions were significant. One was the interaction of condition, response, and orientation, $F(10, 630) = 2.54$, $p < .01$. The interaction between condition and orientation (shown in Fig. 2) was found for both identical and mirror-image pairs, F's$(10, 630) \geq 3.2$, $p < .01$, but was more pronounced on identical pairs. The second interaction was between condition and the sex of the subject, $F(2, 126) = 3.65$, $p < .05$. Males and females performed comparably when accuracy was stressed, $F < 1$ (96.7% correct vs 96.9%). However, females were marginally more accurate than males when speed was stressed, $F(1, 126) = 2.79$, $p < .10$ (86.6% vs 89.7%), and males were more accurate with neutral instructions, $F(1, 126) = 4.56$, $p < .05$ (95.5% vs 91.6%).

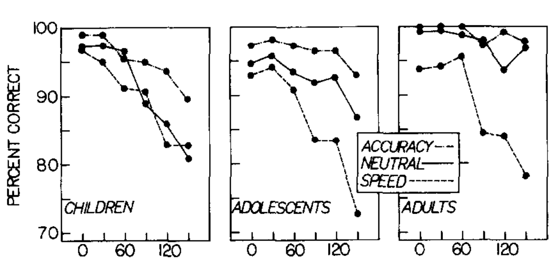

FIG. 2. Accuracy (percentage correct) as a function of the orientation of the comparison stimulus, shown separately for children, adolescents, and adults in the three instructional conditions.

Response times. For each subject, a mean response time was computed for each of the 12 combinations of orientation (6) and response (2), using correct responses only. Shown in Fig. 3 are mean response times as a function of the orientation of the comparison stimulus, separately for the different age groups and instructional conditions. These data were analyzed with a 3 (age) × 3 (condition) × 2 (sex) × 6 (orientation) × 2 (response) analysis of variance. Significant main effects were found for age, $F(2, 126) = 53.61$, condition, $F(2, 126) = 48.55$, response, $F(1, 126) = 291.79$, and orientation, $F(5, 630) = 189.1$, p's $< .01$. These variables were also involved in two interactions found in previous work (Carter et al., 1983). The interaction of age and orientation, $F(10, 630) = 5.93$, $p < .01$, represented the pattern typically used to infer age differences in rate of mental rotation: Although response time increased as a function of orientation at all ages, F's$(5, 630) \geq 37.41$, $p < .01$, the rate of increase was inversely related to age. The interaction of response and orientation was also reliable, $F(5, 630) = 20.56$, $p < .01$. Response time increased as a function of orientation on both identical and mirror-image pairs, F's$(5, 630) \geq 79.35$, $p < .01$, but more rapidly on the former.

As was the case with accuracy, there were several significant interactions involving instructional condition. The interaction between condition and response was significant, $F(2, 126) = 9.07$, $p < .01$, as was the interaction of sex of the subject with these two variables, $F(2, 126) = 3.47$, $p < .05$. Responses to identical pairs were always faster than responses to mirror-image pairs, but the pattern of this difference across conditions differed for males and females. For males, the simple interaction of condition and response was not significant, $F(2, 126) = 1.26$, reflecting the fact that the difference between response times on identical and mirror-image pairs was consistent across conditions. This difference was 263 ms for neutral instructions, 207 ms for speed instructions, and 281 ms for accuracy instructions. In contrast, for females the simple interaction between condition and response was significant, $F(2, 126) = 11.27$, $p < .01$. The difference in response time on identical and mirror-image pairs

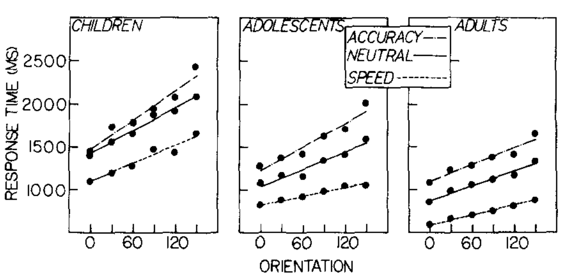

FIG. 3. Response time (in ms) as a function of the orientation of the comparison stimulus, shown separately for children, adolescents, and adults in the three instructional conditions. Also shown for each group is the best-fitting linear function.

was 170 and 154 ms with neutral and speed instructions, respectively, but 361 ms with accuracy instructions. There is no obvious explanation for this pattern. However, these results do underscore the need to consider speed–accuracy trade-offs in the analysis of sex differences in performance on spatial and other speeded tasks.

Of greatest import for the present study was the interaction between condition and orientation, $F(10, 630) = 7.4$, $p < .01$, reflecting the anticipated effect of instructions. Response time increased as a function of orientation for all conditions, F's$(5, 630) \geq 27.85$, $p < .01$, but the rate of increase was fastest for accuracy instructions and slowest for speed instructions, with neutral instructions intermediate. Another way to describe these effects is in terms of the slope and intercept of the best fitting linear equations for the response time functions, shown in Table 1. At all ages, slopes and intercepts were smallest for the speed instructions, followed by the neutral and accuracy instructions.

Isoaccuracy Contours

The general aim of the analyses described here was to derive latency functions in which accuracy was controlled statistically across all orientations and for all groups. Determining such "isoaccuracy contours" (Pachella, 1974) involved several steps. The first was determining the relation between accuracy and latency for each of 18 combinations of age and orientation. For each combination, mean accuracy (percentage correct) and mean response latency were determined for each of the three conditions, separately for males and females (but combined across identical and mirror-image responses). These data are shown in Fig. 4, where mean response time is plotted against mean percentage correct, for each of the six orientations.

The next step involved determining, for each combination of orientation and age, the function that best described increases in mean response time as a function of mean percentage correct. Four functions were

TABLE 1

LEAST SQUARES FUNCTIONS RELATING RESPONSE TIME TO THE ORIENTATION OF THE COMPARISON STIMULUS IN DEGREES

	Condition		
	Accuracy	Neutral	Speed
Children	$5.82X + 1460$ (95)	$4.55X + 1413$ (98)	$3.54X + 1094$ (93)
Adolescents	$4.65X + 1221$ (93)	$3.35X + 1038$ (93)	$1.63X + 832$ (96)
Adults	$3.31X + 1098$ (93)	$2.87X + 875$ (96)	$1.87X + 600$ (98)

Note. Values in parentheses indicate percentage of variance accounted for by the linear equation.

evaluated: linear, exponential, logarithmic, and power. The fit of the data to the four functions was very similar so the most straightforward of the four, the linear, was used in all subsequent analyses. Median values for r^2 for the linear equation (averaged across the six orientations) were .49, .67, and .74 for children, adolescents, and adults.

The best-fitting linear functions are shown in Fig. 4. The slopes of the functions indicate the amount of time needed to increase accuracy 1%. Age differences in the slopes of the functions in Fig. 4 were evaluated with t tests in which the numerator was the difference between a pair of slopes and the denominator was the standard error of the difference between slopes (McNemar, 1969, p. 161). These tests revealed only one marginally significant difference, between adults and adolescents at 60°, $t(8) = 2.08, p < .10$.

The functions depicted in Fig. 4 can be used to derive a predicted response time at various levels of accuracy. This was done for two accuracy criteria, 95 and 100%, values chosen because they encompass a majority of the means for accuracy. Using these accuracy values as the predictor in the speed–accuracy functions shown in Fig. 4 yielded 36 predicted response times (2 error rates × 3 ages × 6 orientations), shown in Fig. 5. Also shown in Fig. 5 are the best-fitting linear functions that relate these response times predicted from percentage correct to the orientation of the comparison stimulus. As before, age differences in the slopes of these functions were evaluated with t tests (with $df = 8$) in which the numerator was the difference between a pair of slopes from

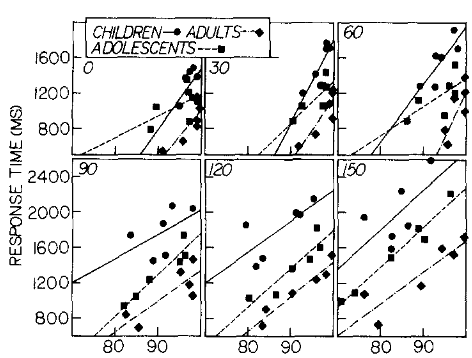

FIG. 4. Response time (in ms) as a function of accuracy (percentage correct), for each of the six orientations of the comparison stimulus (0 to 150°, in increments of 30°). Each point represents the mean percentage correct and mean response time for a group of subjects (e.g., adolescent females who received instructions that emphasized accuracy). Generally, data in the upper right-hand quadrant of each panel are from the condition in which accuracy was emphasized; data in the lower left-hand quadrant are from the condition in which speed was emphasized; data in the center are from the neutral condition. Also shown is the best-fitting linear equation for each age group at each orientation.

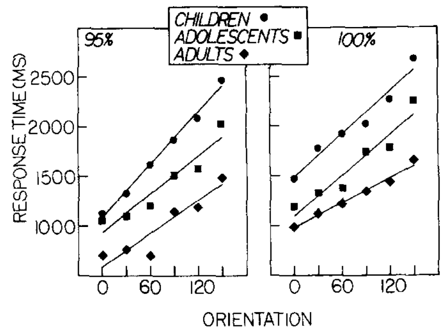

FIG. 5. Predicted response time (in ms) as a function of the orientation of the comparison stimulus, for children, adolescents, and adults. Accuracy was set at 95% and 100% to estimate the response times in the left and right panels, respectively.

Fig. 5 and the denominator was the standard error of the difference between slopes. For the 95% isoaccuracy contour, the slope of the latency function was steeper for children (8.77 ms/deg) than for adolescents (6.3 ms/deg), $t = 2.22$, $p < .05$, one tailed. Slopes for adolescents and adults (5.53 ms/deg) did not differ significantly, $t < 1$. A different pattern emerges for the 100% isoaccuracy contour. Here slopes for children (7.20 ms/deg) and adolescents did not differ (6.82 ms/deg), $t < 1$, but both were significantly larger than slopes for adults (4.22 ms/deg), t's ≥ 2.43, $p < .05$. In short, the pattern of developmental change in rate of mental rotation varied as a function of the accuracy level.

DISCUSSION

One aim of the present study was to determine if speed and accuracy trade off in a regular manner in performance on a mental rotation task. The findings here were straightforward. As shown in Fig. 4, at all ages increases in accuracy occurred at the cost of slower responses. Furthermore, these trade-offs were similar, qualitatively and quantitatively, for the three age groups. These effects occurred because instructions had large and consistent effects on speed of response: At all ages and orientations, responses were fastest for subjects who received instructions that emphasized speed, followed by subjects in the neutral and accuracy conditions (Fig. 3). Instructions were not as uniformly effective in their impact on accuracy. Only adolescents showed the prototypic pattern. For adults, emphasis on accuracy had relatively little influence because adults were already highly accurate in the neutral condition. More interesting is the fact that for children, instructions to respond more rapidly did not result in accuracy below that in the neutral condition. Such an outcome would have entailed near chance levels of performance (at extreme orientations), which children may have viewed as unacceptably poor performance.

Concerning the third question addressed in this study—whether the pattern of developmental change in processing speed depends upon accuracy criteria—the answers are more interesting but considerably more tentative. At the 95% accuracy criterion adults and adolescents mentally rotated stimuli at comparable rates and both were faster than children; at the 100% criterion, adults' mental rotation was significantly faster than that of adolescents and children, who did not differ from one another.

The reason for these differing profiles is found in Fig. 4. Adults (and, to a lesser extent, children) have steeper speed–accuracy gradients for 0 to 60° than they do at orientations greater than 60°; hence, adults' predicted response times are 300–400 ms less for the 95% criterion than for the 100% criterion. The speed–accuracy gradient is relatively shallow when the orientation of the comparison stimulus exceeds 90°. As a consequence, the predicted response times for these orientations are quite similar for the 95 and 100% accuracy criteria. The combined result is that the slope for the adults' predicted response time function is actually steeper at the 95% criterion than at 100% criterion—indicating faster mental rotation at the more stringent accuracy criterion.

For adolescents, speed–accuracy gradients are much the same at all orientations, with the result that their predicted response times are consistently greater at the 100% accuracy criterion by approximately 150–235 ms. These consistent increases in predicted response times mean that the slope of the predicted mental rotation function is essentially the same for the 95 and 100% accuracy criteria.

It would be premature to overemphasize the specific conclusion that mental rotation reaches adultlike speeds in adolescence at 100% accuracy but not 95% accuracy, because of a number of limitations associated with the use of instructions to generate speed–accuracy functions (Wickelgren, 1977). One shortcoming is that subjects are told the desired emphasis on speed and accuracy at the beginning of a block of trials. This raises the possibility that subjects may vary their processing strategies depending upon the speed–accuracy instructions they receive. The fit of the response time data to the Cooper and Shepard model (1973) is good for all conditions (see Table 1), so this does not appear to have been a serious problem in the present study.

A second shortcoming concerning instructions is more troublesome. With the instructions used here it was possible to generate only three distinct points for each speed–accuracy function (each of which was estimated twice, once for males and once for females). This procedure does not lend itself well to determining the precise shape of the speed–accuracy function. Of course, imprecision in the description of the speed–accuracy function results in imprecision in the isoaccuracy contours. The fit of the speed–accuracy data to the linear function was far from perfect, indicating that it would be profitable to pursue other methods for obtaining speed–accuracy data that result in a larger data base from which to estimate the speed–accuracy function. One useful paradigm may be the "response to signal" procedure in which, upon presentation of a signal from the experimenter (e.g., a tone), subjects cease trying to solve the problem and, instead, respond immediately (Dosher, 1981). Speed–accuracy functions can be determined precisely be systematically varying the amount of time between presentation of the target stimuli (e.g., in the present study, a pair of letters) and the signal to respond.

More generally, based on the present findings, it appears that only by considering the level of accuracy associated with a given speed of response can reaction time paradigms be used with confidence to make conclusions regarding cognitive developmental change. It remains to be seen if we must qualify conclusions from other cognitive tasks in which response times have been used to infer patterns of development (e.g., reasoning, memory, and mental arithmetic).

REFERENCES

Ashcraft, M. H. (1982). The development of mental arithmetic: A chronometric approach. *Developmental Review*, **2**, 213–236.

Bisanz, J., Danner, F., & Resnick, L. B. (1979). Changes with age in measures of processing efficiency. *Child Development*, **50**, 132–141.

Carter, P., Pazak, B., & Kail, R. (1983). Algorithms for processing spatial information. *Journal of Experimental Child Psychology*, **36**, 284–304.

Childs, M. K., & Polich, J. M. (1979). Developmental differences in mental rotation. *Journal of Experimental Child Psychology*, **27**, 339–351.

Cooper, L. A., & Shepard, R. N. (1973). Chronometric studies of the rotation of mental images. In W. G. Chase (Ed.), *Visual information processing*. New York: Academic Press.

Dosher, B. A. (1981). The effects of delay and interference: A speed–accuracy study. *Cognitive Psychology*, **13**, 551–582.

Gitomer, D. H., Pellegrino, J. W., & Bisanz, J. (1983). Developmental change and invariance in semantic processing. *Journal of Experimental Child Psychology*, **35**, 56–80.

Kail, R., Pellegrino, J., & Carter, P. (1980). Developmental changes in mental rotation. *Journal of Experimental Child Psychology*, **29**, 102–116.

McNemar, Q. (1969). *Psychological statistics* (4th ed). New York: Wiley.

Pachella, R. G. (1974). The interpretation of reaction time in information processing research. In B. H. Kantowitz (Ed.), *Human information processing: Tutorials in performance and cognition*. Hillsdale, NJ: Erlbaum.

Posner, M. I. (1969). Abstraction and the process of recognition. In J. T. Spence & G. Bower (Eds.), *The psychology of learning and motivation* (Vol. 3). New York: Academic Press.

Sternberg, R. J., & Nigro, G. (1980). Developmental patterns in the solution of verbal analogies. *Child Development*, **51**, 27–38.

Sternberg, R. J., & Rifkin, B. (1979). The development of analogical reasoning processes. *Journal of Experimental Child Psychology*, **27**, 195–232.

Waber, D. P., Carlson, D., & Mann, M. (1982). Developmental and differential aspects of mental rotation in early adolescence. *Child Development*, **53**, 1614–1621.

Wickelgren, W. A. (1977). Speed–accuracy tradeoff and information processing dynamics. *Acta Psychologica*, **41**, 67–85.

RECEIVED: June 14, 1984; REVISED: October 12, 1984, November 8, 1984.